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RESEARCH ARTICLE

Superiority of the Bouyoucos method with sand weighing and the Robinson pipette with a dispersant mixture for quantifying clay in variable-charge acid soils

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Abstract

The Bouyoucos hydrometer method is commonly used to determine the proportional sand, silt, and clay fractions in Peruvian soils. However, this approach often yields variable and imprecise results, particularly in acid soils with variable-charge. This study aimed to evaluate the efficiency of three alternative methods, the Bouyoucos hydrometer method including sand weight (Bhm-sw), the Robinson pipette method (Rpm), and the Robinson pipette method using a mixture of dispersing agents (Rpm-md), compared with the standard Bouyoucos hydrometer method (Bhm). Soil samples were collected from the first three horizons of profiles developed on the Sarayaquillo, Chonta, Chambara, and Oriente Group lithostratigraphic formations. The data was first tested for normality using the Shapiro-Wilk test. Non-parametric data were transformed into parametric variables through quantile normalization, then used analysis of variance and Dunnett's test to compare the alternative methods with the standard method. Method efficiency was assessed by the highest recovery of the clay fraction. The results showed that the standard Bouyoucos hydrometer method was not efficient for clay fraction determination, as Bhm-sw ($p < 0.01$) and Rpm-md ($p < 0.05$) significantly outperformed it, increasing the clay fraction by 15.51% and 11.55%, respectively. These findings suggest both methods may be suitable for laboratory use in other soil classes common in the Peruvian Amazon. The efficiency ranking of the evaluated methods was Bhm-sw > Rpm-md > Bhm = Rpm.

Keywords: Texture analysis; Bouyoucos hydrometer; Robinson pipette; chemical dispersants; variable-charge acid soil, clay quantification.

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1. Introduction

Soil texture, defined in the textural triangle by the relative proportions of sand, silt, and clay particles, is an inherent soil property that external factors do not easily modify (Corá et al., 2009). It directly influences infiltration capacity, water availability, and carbon storage capacity (Callesen et al., 2003), as well as nutrient dynamics (Mozaffari et al., 2024). Therefore, this property widely guides soil use and management practices across agricultural, forestry, and livestock production systems, particularly for fertilization, acidity correction, and studies of soil genesis and classification (Mauri et al., 2011). These applications are largely based on clay content (Tavares-Filho & Magalhães, 2008), since clay has a greater specific surface area than other particle-size fractions and a higher ion-exchange capacity. Consequently, soil texture is an important attribute for plant development and productivity (Mwendwa, 2022).

Particle-size analysis is commonly performed based on the principle of particle sedimentation described by Stokes' law (Alves et al., 2018; Callesen et al., 2023; Messing et al., 2024). Among these methods, the Robinson pipette method (Rpm) has shown greater accuracy and precision, particularly for quantifying the clay fraction. However, its application is limited by operational complexity, the time required to obtain results, and the need for exhaustive pretreatments (Schlindwein et al., 2011), such as

the removal of organic matter, iron oxide compounds, and exchangeable aluminum, which promote flocculation processes and the formation of highly stable aggregates that are difficult to disperse (Suzuki et al., 2015). In contrast, the Bouyoucos hydrometer method (Bhm) is widely adopted because it is easy to implement, fast to perform (Beretta et al., 2014), and cost-effective. It is also used as a standard method in routine analyses (Curcio et al., 2013) and for taxonomic classification. However, its use for this purpose is not recommended because incomplete aggregate dispersion limits accuracy (Faé et al., 2019; Mozaffari et al., 2024; Owji et al., 2014). This limitation may overestimate the silt fraction and underestimate the clay fraction, producing erroneous textural results (García et al., 2008).

Accordingly, the precision of particle-size analysis depends on the method used, the chemical dispersants applied, and the duration of mechanical agitation, all of which must promote aggregate dispersion and/or breakdown while maintaining particles in suspension throughout the analytical process (Mauri et al., 2011; Ruiz, 2005). Sodium-containing chemical dispersants are among the most widely used because they can more effectively replace flocculating cations such as Ca^{2+}, Mg^{2+}, and Al^{3+} from cation-exchange sites (Borja et al., 2015). Sodium hydroxide (NaOH), widely used in tropical soils with Rpm, has been more effective at dispersing pH-dependent clays (Cunha et al., 2014; Júnior et al., 2014). In contrast, sodium hexametaphosphate ($(NaPO_3)_6$) is more efficient in soils with high contents of alkaline-earth cations, as it reduces osmotic pressure and precipitates phosphates associated with Ca^{2+} and Mg^{2+} (Camargo et al., 2009).

Because the Bhm is widely adopted as the standard method in soil testing laboratories in Peru, even for taxonomic purposes, it is necessary to evaluate its performance against alternative methods to improve result accuracy. Currently, information on these methods' performance in variable-charge acid soils with a kaolinite-dominated mineral fraction remains limited. Therefore, the objective of this study was to evaluate the efficiency of the modified Bouyoucos hydrometer method, which incorporates the weight of the sand fraction (Bhm-sw), the Rpm using only sodium hydroxide (NaOH) as a chemical dispersant, and its variant using the combination of NaOH + $(NaPO_3)_6$, in comparison with the standard Bmh for determining the particle-size fractions in soils from the Leoncio Prado province, Huanuco region.

2. Methodology

2.1. Study area and experimental site

The soil sampling points were in Leoncio Prado province, Huanuco, in quadrangle 19-k, and covered areas associated with the Chambara Formation, Oriente Group, Chonta Formation, and Sarayaquillo Formation (Figure 1).

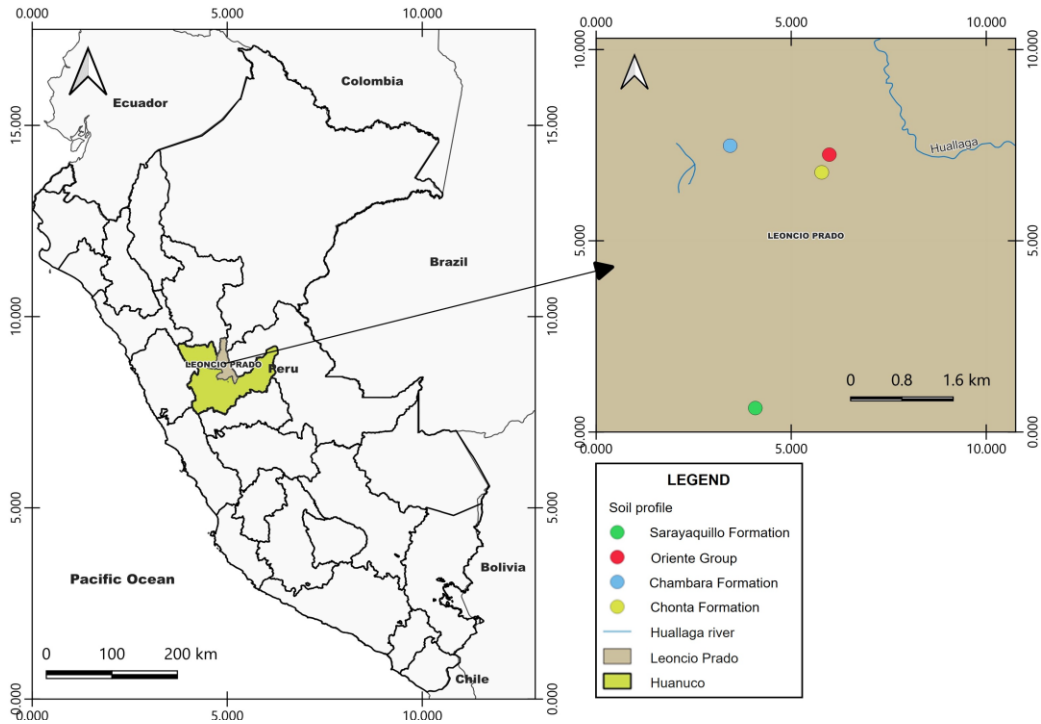


Figure 1. Location map of the soil sampling points and the corresponding lithostratigraphic units.

These areas lie within the Rupa Rupa or High Jungle natural region, at elevations ranging from 660 to 1 300 m a. s. l. The area has a mean annual precipitation of 3 100 mm, temperatures ranging from 18.7 to 30.3 °C, and high relative humidity throughout the year. It corresponds to a Tropical Premontane Very Humid Forest zone (bmh-MT), transitional to Tropical Very Humid Forest (bmh-PT/T). Hydrologically, the sampling points are located within the Huallaga River basin and the Monzón River sub-basin (Martínez et al., 1998).

2.2. Soil sampling and lithological characterization

Soil sampling was conducted to account for the variability of the lithostratigraphic units identified in the study area (Martínez et al., 1998) (Table 1). This approach was adopted because the parent material, in interaction with the area's climatic conditions, influences soil genesis and the variability of its physical and chemical properties.

In each lithostratigraphic unit, a soil pit was excavated for the morphological description of the profile. Subsequently, soil samples were then collected from the first three genetic horizons. The samples were labeled and processed for physical and chemical analyses at the Soil, Water, and Ecotoxicology Analysis Laboratory and at the Soil Conservation Laboratory of the Universidad Nacional Agraria de la Selva (UNAS), in Tingo Maria, Huanuco.

The particle-size analysis was performed on all sampled genetic horizons to evaluate the effect of textural methods and their variants under conditions representative of a soil analysis laboratory, where prior information on the soil or horizon of origin is generally unavailable. This approach allowed for an integrated evaluation of the data and greater generalization of the conclusions obtained.

2.3. Soil chemical analysis

Soil pH was determined in H_2O and in 0.5 mol L^{-1} KCl at a 1:2.5 soil:solution ratio using a potentiometric method, with the pH meter properly calibrated with pH 4.0 and 7.0 standard buffer solutions. Exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+} were extracted with 1 mol L^{-1} KCl, whereas K^+ and Na^+ were extracted with 1 mol L^{-1} NH_4OAc at pH 7.0. Potential acidity (H + Al) was extracted with a 0.5 mol L^{-1} $Ca(CH_3COO)_2$ solution at pH 7.0.

Calcium and magnesium concentrations were determined by titration with 0.0125 mol L^{-1} EDTA (EMBRAPA, 2017), whereas K^+ and Na^+ were quantified by atomic absorption spectrometry. Exchangeable Al^{3+} and H + Al were quantified by titration with 0.025 mol L^{-1} NaOH. Organic carbon content was determined according to the Walkley and Black method (Walkley & Black, 1934).

2.4. Particle-size analysis

2.4.1. Bouyoucos hydrometer method (Bhm)

Particle-size quantification followed the standard procedure of the Soil, Water, and Ecotoxicology Analysis Laboratory at the Universidad Nacional Agraria de la Selva. Briefly, 50 g of air-dried soil, previously passed through a 2 mm sieve, was placed in a glass container, followed by the addition of 15 mL of 10% sodium hexametaphosphate ($(NaPO_3)_6$) and 150 mL of distilled water. The suspension was then mechanically shaken for 1 h on a vertical shaker at 50 rpm to ensure adequate dispersion of the soil particles.

Subsequently, the suspension was transferred to a 1 L graduated cylinder, and the final volume was brought to 1 L with distilled water. The mixture was manually homogenized using a wooden rod, and after 40 s, the first hydrometer reading was taken to estimate the sand fraction (Equation 1). After 2 h of sedimentation, a second reading was taken to estimate the clay fraction (Equation 2). Finally, the silt fraction was calculated by the difference between the two measurements (Equation 3).

$$\% \text{ Sand} = 100 - ((R_{40s} \times 2)/Md)*100 \quad \text{(Eq. 1)}$$

$$\% \text{ Clay} = ((R_{2h} \times 2)/M_d)*100 \quad \text{(Eq. 2)}$$

$$\% \text{ Silt} = 100 - \% \text{ Sand} - \% \text{ Clay} \quad \text{(Eq. 3)}$$

Where: R_{40s} is the hydrometer reading after 40 s, R_{2h} is the hydrometer reading after *2h*, and M_d is the dry soil mass.

2.4.2. Bouyoucos hydrometer method with sand fraction weight (Bhm-sw)

Following the standard Bhm procedure described above, the sand fraction was separated after mechanical shaking by passing the suspension through a 0.053 mm sieve (Figure 2), which was initially placed in a funnel coupled to a 1 L graduated cylinder. This allowed only the silt and clay fractions remaining in suspension to pass directly into the cylinder for subsequent estimation.

Table 1
Distribution of the analyzed samples according to lithostratigraphic unit within the Mesozoic Erathem

Erathem	System	Series	Lithostratigraphic Unit	Symbol
Mesozoic	Cretaceous	Lower	Chonta Formation	Kis-ch
			Oriente Group	Ki-o
	Jurassic	Upper	Sarayaquillo Formation	Js-s
	Triassic	Upper	Chambara Formation	Trji-ch

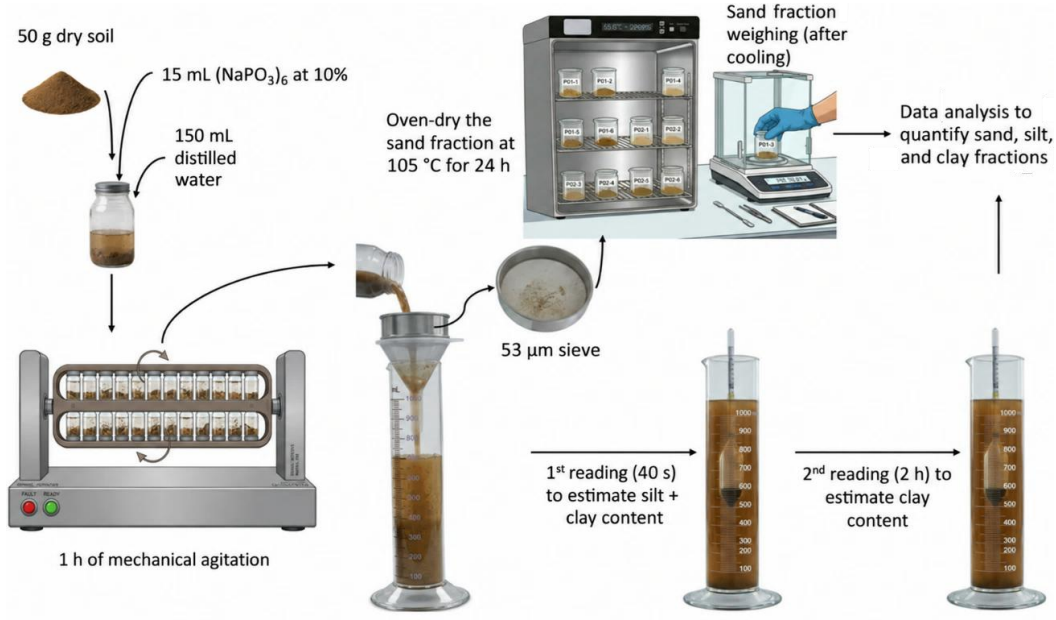


Figure 2. Bhm-sw protocol for soil particle-size determination via 53 µm sieving, oven-drying, and weighing of the sand fraction.

The sand retained on the sieve was transferred to a previously tared 50 mL beaker (precision 0.0001 g) and oven-dried at 105 °C for 24 h. Subsequently, the sample was then cooled in a desiccator for 30 min and weighed with a precision of 0.0001 g. The silt and clay fractions were estimated according to the standard Bhm procedure.

Additionally, for the precise quantification of the sand fraction, the correction factor *f* was determined. This factor was used to correct the soil analysis results. For this purpose, 20 g of air-dried soil were weighed with a precision of 0.0001 g (M_{ads}) in a previously tared container, also with a precision of 0.0001 g. The samples were then oven-dried at 105 °C for 12 h (M_{od}), removed from the oven, placed in a desiccator until room temperature, and finally weighed to 0.0001 g. The correction factor was calculated according to Equation 4.

$$F = (M_{ads}/M_{od}) \quad \text{(Eq. 4)}$$

Thus, the sand fraction was quantified as a percentage according to the procedure suggested by Ruiz (2005), as shown in Equation 5:

$$\%X_{Ao} = (M_{ods} + (1/\boldsymbol{M}_{adfs}) * f) *100 \quad \text{(Eq. 5)}$$

Where: $\%X_{Ao}$ = sand percentage; M_{ods} = oven-dried sand mass (g); M_{adfs} = air-dried fine soil mass (g); *f* = correction factor; and 100 = conversion factor used to express the result as a percentage.

2.4.3. Robinson pipette method (Rpm)

The method was performed as described by Ruiz (2005). Briefly, 10 g of air-dried soil, previously passed through a 2 mm sieve, was placed in a 250 mL beaker, then 50 mL of 0.1 mol L^{-1} NaOH and 150 mL of distilled water were added. The sample was then left to stand for 6 h and subsequently placed in a vertical mechanical shaker at 50 rpm for 16 h.

After mechanical shaking, the sand fraction was separated by passing the soil suspension through a 0.053 mm sieve placed on a funnel coupled to a 500 mL graduated cylinder. The retained sand fraction was transferred to a previously tared 50 mL beaker (± 0.0001 g), and the excess water was removed, and the sample was oven-dried at 105 °C for 12 h. Finally, the sample was cooled in a desiccator for 30 min and weighed on an analytical balance with a precision of 0.0001 g. The sand fraction was quantified according to Equation 5.

The silt and clay fractions were determined in a 500 mL graduated cylinder previously filled to volume with distilled water. The suspension was manually agitated for approximately 20 s with a wooden rod and, immediately afterward, 25 mL of the silt + clay suspension was collected using a calibrated pipette inserted to a depth of 5 cm. The collected volume was transferred to a previously tared 50 mL beaker (± 0.0001 g) and oven-dried at 105 °C for 48 h. After drying, the samples were cooled in a desiccator for 30 min and then weighed with the same precision. The silt plus clay fraction was quantified according to Ruiz (2005), as shown in Equation 6.

$$\%X_{(silt + clay)} = ((M_{(silt + clay + d)} - M_d)*(V_t/V_c)*(1/M_{adfs})*f)*100 \quad \text{(Eq. 6)}$$

Where: $\%X_{(silt + clay)}$ = percentage of silt + clay; $M_{(silt + clay + d)}$ = mass of silt + clay + dispersant (g); M_d = mass of the dispersant (0.010 g); V_t = total volume of the suspension in the graduated cylinder (mL); V_c = volume collected with the pipette (mL); M_{adfs} =

mass of air-dried fine soil (g); and *f* = correction factor.

The clay fraction was determined from the remaining suspension (475 mL) after recording the solution temperature. Based on Stokes' law and considering the time required for silt sedimentation within the upper 5 cm of the graduated cylinder (Table 2), the suspension was agitated for 20 s using a glass rod and then allowed to stand for the estimated sedimentation time.

After this interval, a calibrated 25 mL pipette was carefully inserted to a depth of 5 cm, and the suspension corresponding to the clay fraction was collected. The aliquot was transferred to a previously tared 50 mL beaker (±0.0001 g) and oven-dried at 105 °C for 48 h. Finally, the samples were cooled in a desiccator and weighed with a precision of 0.0001 g.

The clay fraction was quantified according to Ruiz (2005), as shown in Equation 7.

$$\%X_{clay} = ((M_{(clay+d)} - M_d) * (V_t/V_c)*(1/M_{adfs})*f)*100 \quad \text{(Eq. 7)}$$

Where: $\%X_{clay}$ = percentage of clay; $M_{(clay+d)}$ = mass of clay + dispersant (g); M_d = mass of the dispersant (0.0100 g); V_t = total remaining volume of the suspension in the graduated cylinder (mL); V_c = volume collected with the pipette (mL); M_{adfs} = mass of air-dried fine soil (g); and *f* = correction factor.

Additionally, to ensure the sand, silt, and clay fractions summed to 100%, the difference was proportionally distributed among the fractions, as suggested by Ruiz (2005), according to Equations 8, 9, and 10.

$$\%Sand: (X_{Sand} / \Sigma Sand + Silt + Clay)*100 \quad \text{(Eq. 8)}$$
$$\%Silt: (X_{Silt} / \Sigma Sand + Silt + Clay)*100 \quad \text{(Eq. 9)}$$
$$\%Clay: (X_{clay} / \Sigma Sand + Silt + Clay)*100 \quad \text{(Eq. 10)}$$

Where: X_{Sand} = calculated sand proportion; X_{silt} = silt proportion; X_{clay} = clay proportion; and ∑Sand + Silt + Clay = sum of all textural fractions.

2.4.4. Robinson pipette method with a mixture of dispersants (Rpm-md)

For this procedure, the same protocol previously described for the Rpm was followed, with the only modification being the dispersant used. A mixture of 0.1 mol L^{-1} NaOH + 0.016 mol L^{-1} sodium hexametaphosphate ($(NaPO_3)_6$) was used because this combination proved to be efficient in dispersing clay in electronegative soils (Rodrigues et al., 2011).

2.5. Statistical analysis

Statistical analyses were performed using RStudio software. Data from four replicates for each method were evaluated using the Shapiro-Wilk normality test. Data that did not meet the normality assumption were transformed using quantile normalization. Subsequently, analysis of variance (ANOVA) and Dunnett's test were applied, with mean comparisons at the 5% and 1% significance levels, to identify statistically significant differences between the alternative methods and the standard method.

3. Results and discussion

3.1. Soil chemical analysis

Overall, soils developed on the Sarayaquillo Formation (Js-s), Chonta Formation (Kis-ch), Chambara Formation (Trji-ch), and Oriente Group (Ki-o) showed pHH_2O values from 4.28 to 4.69 and KCl values from 3.58 to 4.03 (Table 3). This strongly acidic condition is characteristic of humid tropical environments, where intense weathering leaches basic cations and 1:1-type minerals predominate (De Souza et al., 2018; Quesada et al., 2010).

The negative pH differential between the two measurements ($pH_{KCl} - pHH_2O$), ranging from -0.39 to -0.98, indicates the predominance of permanent and variable negative charges associated with low-activity clays and organic matter (OM), as well as a high proportion of adsorbed H^+ and Al^{3+}. These values were more negative in the Js-s and Kis-ch formations, reflecting greater exchangeable acidity intensity due to continuous leaching of exchangeable bases.

OM content showed a clear vertical variation, with higher values in the surface Ap and A horizons (1.88-2.96%), followed by a progressive decrease in the subsurface AB, BA, Bw, and B horizons. This pattern reflects surface accumulation of plant residues and their rapid mineralization under tropical conditions of high temperature and humidity (De Souza et al., 2018), typical of the study area. In this context, OM contents below 5% support the direct application of the methods used without prior OM removal, as proposed by Kalra and Maynard (1991). Similarly, low Ca^{2+} and Mg^{2+} concentrations (< 1 $cmol_c\ kg^{-1}$) were observed in the Js-s, Kis-ch, and Ki-o formations, limiting both chemical fertility and buffering capacity against acidity. However, the Trji-ch formation showed high Ca^{2+} values, which may be related to residual influence from carbonate parent material. Nevertheless, this condition was not maintained with depth, indicating that pedogenetic processes exceeded the buffering capacity of the limestones and dolomites characteristic of this formation (Martínez et al., 1998).

Exchangeable aluminum (Al^{3+}) and potential acidity (Al + H) reached high values in almost all horizons, particularly in the subsurface Bw and B horizons.

Table 2
Sedimentation time of particles with a specific gravity of 2.60 g cm^{-3} and a diameter smaller than 0.002 mm as a function of temperature for clay fraction collection at a depth of 5 cm from the upper level of the suspension

Temperature °C	Sedimentation time (h:min)	Temperature °C	Sedimentation time (h:min)
15	04:23	23	03:36
16	04:16	24	03:31
17	04:10	25	03:26
18	04:04	26	03:21
19	03:58	27	03:17
20	03:52	28	03:13
21	03:46	29	03:09
22	03:41	30	03:05

Source: Ruiz (2003).

Table 3
Results of the chemical analysis of soils from the studied lithostratigraphic formations

Formation	Horizons	OM	pH		ΔpH	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	Al^{3+}	Al + H [1]	CECe [2]	CECt [3]	Al Sat [4]
			H_2O	KCl										
		%	1:2.5			----------$cmol_c\ kg^{-1}$----------								%
Js-s	Ap	2.96	4.36	3.76	-0.6	0.75	0.25	0.16	0.05	4.21	11.40	5.21	12.40	80.22
	AB	1.82	4.43	3.86	-0.57	0.50	0.00	0.13	0.05	4.70	10.40	5.20	10.90	89.87
	B1	0.91	4.64	4.02	-0.62	0.50	0.00	0.11	0.07	3.82	8.20	4.32	8.70	87.82
Kis-ch	Ap	2.52	4.34	3.58	-0.76	0.71	0.71	0.22	0.06	5.98	13.30	7.49	14.76	79.82
	BA	1.64	4.69	3.71	-0.98	0.50	0.60	0.15	0.04	6.37	10.50	7.49	11.62	85.03
	Bw1	0.85	4.55	3.72	-0.83	0.50	0.10	0.12	0.04	6.96	10.60	7.58	11.25	91.77
Trji-ch	A	2.42	4.42	4.03	-0.39	4.25	1.50	0.17	0.06	2.06	10.60	7.81	16.35	26.23
	BA	1.40	4.38	3.86	-0.52	3.50	1.50	0.15	0.05	4.80	13.10	9.80	18.10	48.84
	BW1	0.84	4.28	3.85	-0.43	2.00	0.75	0.16	0.04	6.17	11.40	8.92	14.15	68.95
Ki-o	Ap	1.88	4.50	3.92	-0.58	1.00	0.25	0.17	0.07	7.94	13.40	9.19	14.65	86.03
	Bw1	0.75	4.60	3.96	-0.60	1.00	0.00	0.15	0.08	10.29	13.50	11.29	14.50	90.90
	Bw2	0.52	4.68	4.02	-0.66	0.50	0.25	0.11	0.07	9.90	12.60	10.65	13.35	92.70

1/ Potential acidity; 2/ Effective cation exchange capacity; 3/ Cation exchange capacity; and 4/ Aluminum saturation percentage.

Consequently, these soils showed high aluminum saturation (%Al saturation) on most horizons, frequently exceeding 80 %. This implies phytotoxic risk and potential restrictions on plant root development. In contrast, the A horizon of Trji-ch showed notably lower %Al saturation (~26 %), coinciding with higher Ca^{2+} contents and a relatively higher CECt, reflecting more favorable chemical conditions at the soil surface.

3.2. Textural analysis

The mean results (n = 4) for the proportions of sand, silt, and clay on each horizon of the soils developed on the Js-s, Kis-ch, Trji-ch, and Ki-o lithostratigraphic formations, according to each particle-size analysis method used (Bhm, Bhm-sw, Rpm and Rpm-md) (Figure 3), showed textural variability associated with the parent material, soil horizon, and methodological approach.

In the Js-s formation, the surface Ap and AB horizons showed similar sand and clay proportions, whereas the B1 horizon showed increased clay content. This vertical pattern is consistent with clay illuviation (Chittleborough et al., 1984; Pal, 2021), a pedogenetic process characteristic of soils subjected to intense leaching in humid tropical environments.

However, the methods yielded contrasting results. While Bhm-sw significantly increased the clay fraction compared with Bhm, the Rpm and Rpm-md showed, on several horizons, a significant decrease in clay, accompanied by increases in sand and silt. This may relate to the higher osmotic pressure of the solution in Rpm and Rpm-md, which may have induced soil particle flocculation, thereby reducing dispersant efficiency (Cunha et al., 2014).In soils from the Trji-ch formation, all horizons showed higher clay contents, which increased progressively with depth. In these soils, the alternative Bhm-sw and Rpm-md produced highly significant increases (p < 0.01) in the clay fraction compared with the standard method, particularly in the BA and Bw1 horizons. These results indicate that direct weighing of the sand fraction in Bhm-sw and the combination of dispersants in Rpm-md enabled the release of fine particles previously retained within microaggregates while maintaining them dispersed throughout the analytical procedure (Oliveira et al., 2002).

A similar pattern was observed in soils from the Kis-ch formation, where clay content was higher on all horizons and increased significantly when Bhm-sw and Rpm-md were used. The marked response of these soils to the alternative methods suggests that the clay fraction is highly sensitive to dispersion efficiency, consistent with advanced weathering of parent material under tropical conditions (De Souza et al., 2018; Quesada et al., 2010). The reduction in the sand fraction recorded with these methods supports the hypothesis that Bhm tends to overestimate coarser fractions under incomplete dispersion (Mwendwa, 2022).

Soils from Ki-o showed higher sand proportions in the surface horizons that decreased with depth, whereas clay content increased in the Bw1 and Bw2 horizons. Although the alternative methods significantly reduced the sand fraction compared with Bhm, only Bhm-sw and Rpm-md showed a significant increase in the clay fraction (p < 0.01).

Accordingly, Figure 3 shows that Bhm-sw and Rpm-md tended to record significant increases in the clay fraction compared with Bhm in most formations and horizons (p < 0.05; p < 0.01). This response is expected when the methodological treatment improves dispersion and releases fine fractions previously retained within aggregates. Likewise, redistribution in particle quantification using the alternative methods occurred mainly toward the silt fraction, suggesting that methodological differences affect the sand–silt boundary more strongly than the clay fraction. This behavior has previously been reported for soils with relatively homogeneous particle-size distributions (Beretta et al., 2014).

When textural classification was performed (Figure 4), the soil samples were classified differently depending on the method used. Bhm classified 66.66% of the samples as clayey, whereas Bhm-sw and Rpm-md classified 75% as clayey, and Rpm classified only 50%. Nevertheless, both Bhm-sw and Rpm-md showed a shift of the data points toward higher clay contents, maintaining a tendency to classify the soil samples into finer textural classes. These results show that the choice of analytical method affects the accuracy of soil texture determination, a key attribute for interpreting soils' physical and chemical properties.

The mean results (n = 12) for the proportions of sand, silt, and clay in soils from the Js-s, Kis-ch, Trji-ch, and Ki-o lithostratigraphic formations, according to each particle-size analysis method used (Figure 5), showed that the analytical method had a significant effect on the estimation of textural fractions, with differentiated responses depending on the geological formation and intrinsic soil properties.

In the Js-s formation, the results showed that the alternative methods did not statistically outperform the standard method (Bhm) in determining the sand fraction. Conversely, Rpm and Rpm-md recorded a significant decrease in the clay fraction,

accompanied by an increase in silt, indicating that these methods were less efficient at releasing fine particles in this soil. This response may be associated with stable aggregation induced by the presence of iron oxides (García et al., 2008), which have been reported in soils from this formation (Rodríguez et al., 2017). In addition, several studies have documented that, even in soils with moderate OM contents, persistent microaggregates can form and sediment as coarser particles, leading to an apparent underestimation of the clay fraction when dispersion is incomplete (Acevedo et al., 2021; Jensen et al., 2017; Mozaffari et al., 2024).

However, in soils from the Kis-ch and Trji-ch formations, the Bhm-sw showed highly significant increases ($p < 0.01$) in clay content compared with the standard method, accompanied by a decrease in the sand fraction. This result confirms that directly weighing the sand fraction in Bhm-sw provides a more realistic estimate of the fine fractions. Nevertheless, incomplete recovery of sand particles during sieving may also affect the total mass used to calculate the proportions, thereby influencing the increase in the silt and clay fractions.

For the Ki-o soil, none of the alternative methods statistically outperformed Bhm in quantifying the clay fraction. However, the sand fraction decreased significantly, mainly accompanied by increases in silt, indicating a preferential redistribution of intermediate-sized particles (Beretta et al., 2014).

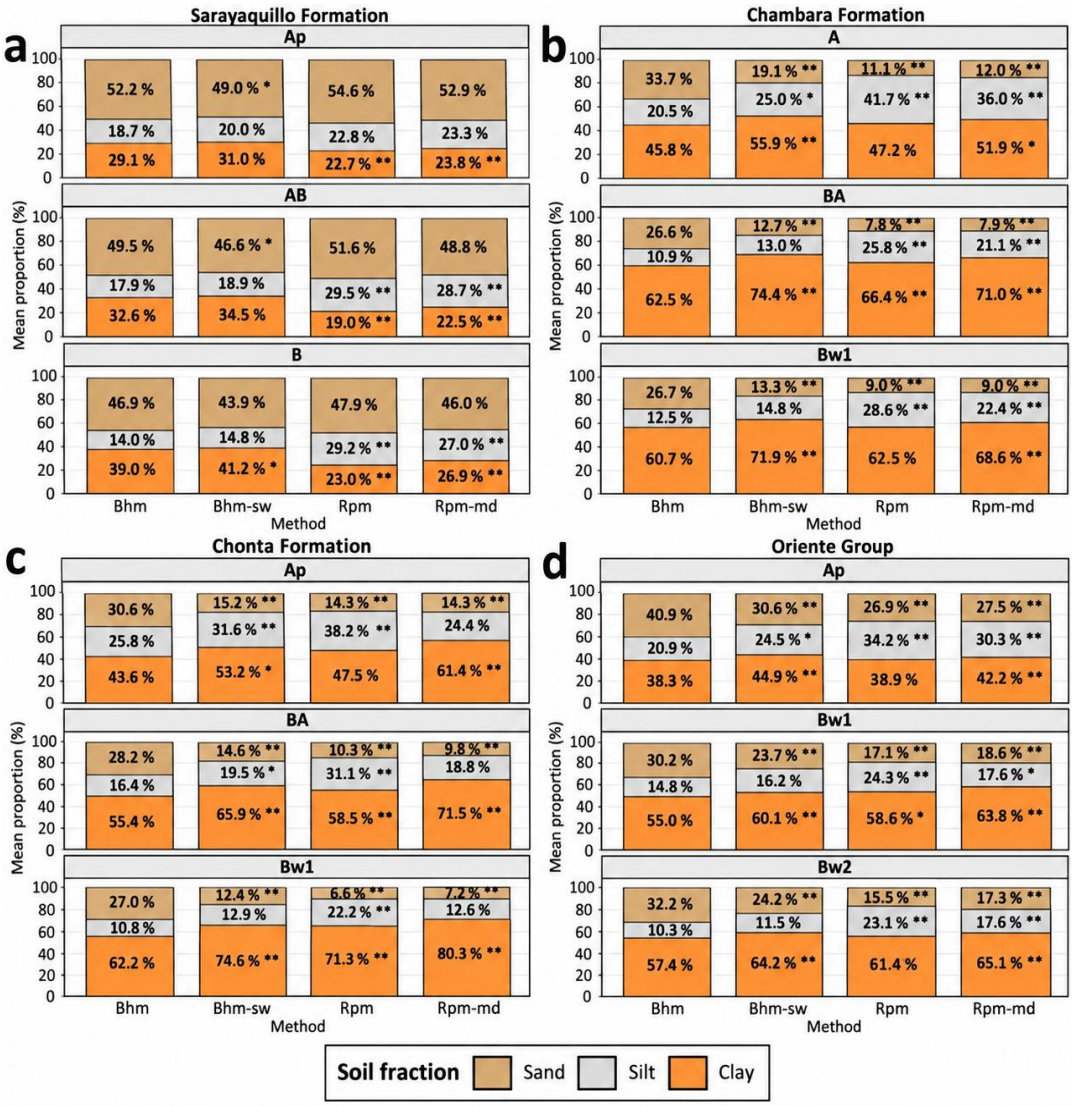


Figure 3. Mean proportion (n = 4) of sand, silt and clay on each horizon of the soils analyzed, across the four methods evaluated in four soil formations: a. Sarayaquillo Formation (Js-s), b. Chambara Formation (Trji-ch), c. Chonta Formation (Kis-ch) and d. Oriente Group (Ki-o). Asterisks indicate statistically significant differences at the 5 % (*) and 1 % (**) levels, respectively, according to Dunnett's test comparing the alternative methods (Bhm-sw, Rpm and Rpm-md) against the standard method (Bhm). Bhm: Bouyoucos hydrometer method; Bhm-sw: Bouyoucos hydrometer method with sand weight; Rpm: Robinson pipette method; Rpm-md: Robinson pipette method with a mixture of dispersants.

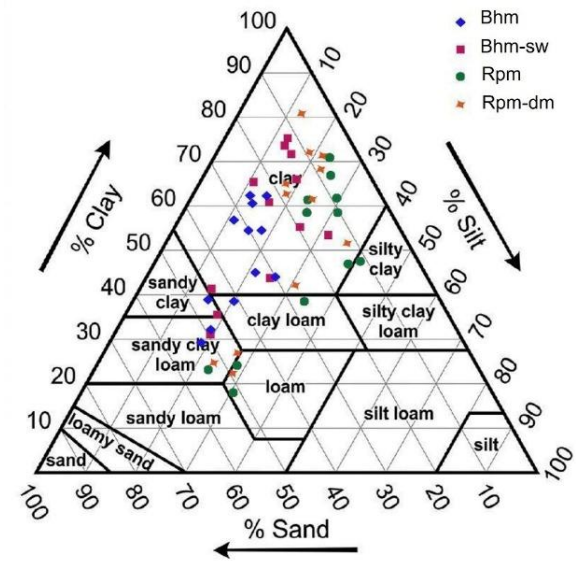


Figure 4. Distribution of soil texture in the USDA textural triangle based on the Bouyoucos hydrometer method (Bhm), the Bouyoucos hydrometer method with sand fraction weight (Bhm-sw), the Robinson pipette method (Rpm) and the Robinson pipette method with a mixture of dispersants (Rpm-md), using the mean values (n = 4) of the 12 soil samples analyzed.

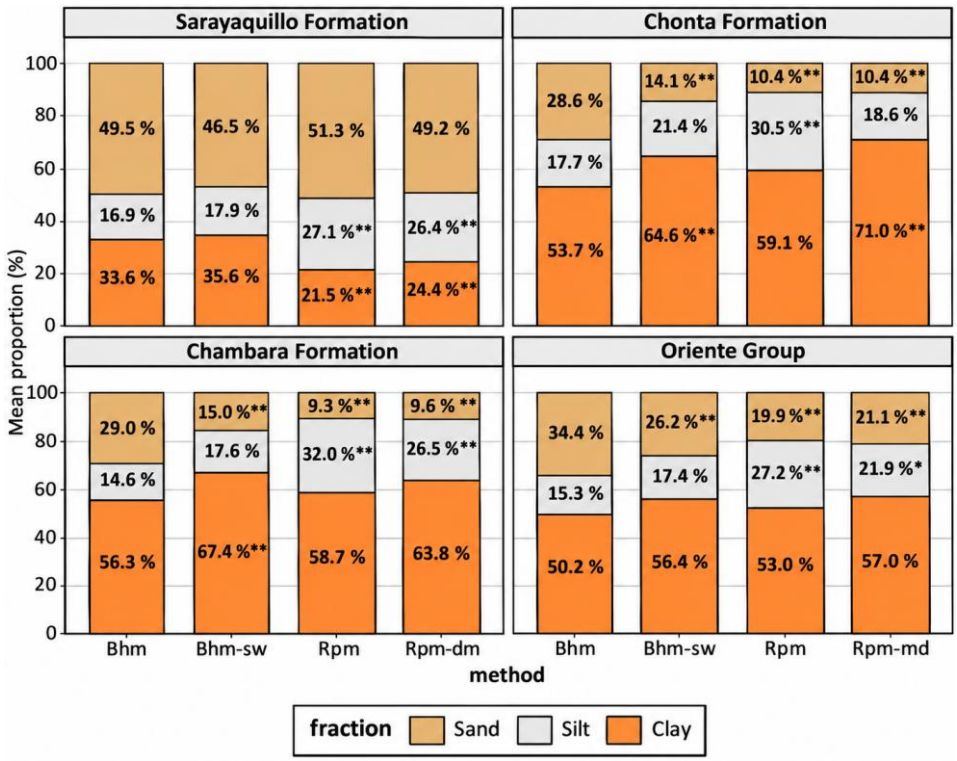


Figure 5. Mean proportion (n = 12) of sand, silt and clay across all horizons in each of the four soil formations, considering the four methods evaluated. Asterisks indicate statistically significant differences at the 5 % (*) and 1 % (**) levels, respectively, according to Dunnett's test comparing the alternative methods (Bhm-sw, Rpm and Rpm-md) against the standard method (Bhm). Bhm: Bouyoucos hydrometer method; Bhm-sw: Bouyoucos hydrometer method with sand weight; Rpm: Robinson pipette method; Rpm-md: Robinson pipette method with a mixture of dispersants.

Overall, the results in Figure 5 confirm that methodological response depends on soil type and that no method is universally superior. However, the consistent increases in clay content obtained with Bhm-sw in fine-textured and highly weathered soils suggest an analytical advantage of Bhm-sw over the standard method, as it reduces the underestimation of fine fractions associated with

incomplete dispersion. In soils from the Js-s formation, where this advantage was not observed, additional adjustments may be necessary, such as pretreatments to oxidize OM and remove iron oxides (Donagemma et al., 2008; Fisher et al., 2017; Kraemer et al., 2016; Zimmermann & Horn, 2020).

Likewise, to identify the most efficient method and the one providing the most robust data for soil textural analysis under real laboratory operating conditions, an integrated mean analysis (n = 48) of the sand, silt, and clay proportions was performed, considering all soils, horizons, and methodologies evaluated (Figure 6). This analysis is relevant because soil testing laboratories generally lack information on the edaphic nature or horizon of origin of samples, which often reflect mixtures of A and B horizons, a common situation in agricultural soil sampling.

The results indicate that all alternative methodologies (Bhm-sw, Rpm and Rpm-md) recorded significantly lower sand proportions (p < 0.01) than the standard method, confirming that Bhm tends to overestimate the sand fraction when dispersion is incomplete. However, the significant increase in the clay fraction, which represents the main methodological challenge in particle-size analysis and is considered the primary indicator of analytical efficiency (Donagemma et al., 2008; Mauri et al., 2011), was observed only with Bhm-sw (p < 0.01) and Rpm-md (p < 0.05), both of which were statistically superior to Bhm (Figure 6).

This behavior can be explained by methodological modifications in the chemical dispersion process and in quantifying the particle-size fractions. In Bhm-sw, the sand fraction was determined by direct weighing, which reduced the cumulative error associated with the indirect estimation used in Bhm and improved redistribution of the fine fractions. This is because the systematic error of Bhm increases as actual sand content decreases, as undispersed aggregates settle as coarse particles (Ashworth et al., 2001; Gee & Bauder, 1979; Papuga et al., 2018).

In Rpm-md, the NaOH + $(NaPO_3)_6$ dispersant mixture promoted more efficient dispersion of colloidal particles, resulting in a significant increase in the clay fraction. This effect, widely reported for tropical and subtropical soils, is attributed to combining an alkaline dispersant with a complexing agent, which increases electrostatic repulsion among particles and disrupts stable organo-mineral bonds (Borja et al., 2015; Combatt-Caballero et al., 2018; Cunha et al., 2014).

Soil particle dispersion does not depend exclusively on Na^+. The presence of associated counterions, such as hydroxides, hexametaphosphates, and carbonates, is also important because they neutralize H^+, Al^{3+}, and Fe^{3+} ions. This increases the density of negative charges on colloidal surfaces, enhancing particle repulsion and maintaining particles dispersed (Mauri et al., 2011). This mechanism is particularly relevant in the evaluated soils, which showed acidic pH, high aluminum saturation, and exchange complexes dominated by negative charges (Table 3), conditions typical of highly weathered soils.

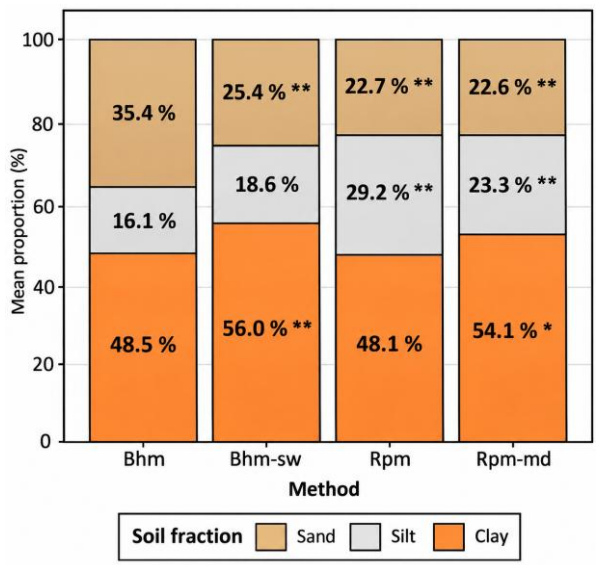


Figure 6. Mean proportion (n = 48) of sand, silt and clay across all soils and horizons analyzed, for the four methods evaluated. Asterisks indicate statistically significant differences at the 5% (*) and 1% (**) levels, respectively, according to Dunnett's test comparing the alternative methods (Bhm-sw, Rpm and Rpm-md) against the standard method (Bhm). Bhm: Bouyoucos hydrometer method; Bhm-sw: Bouyoucos hydrometer method with sand weight; Rpm: Robinson pipette method; Rpm-md: Robinson pipette method with a mixture of dispersants.

Dunnett's test, used to compare multiple treatments against a single control (Rodrigues et al., 2011; Suzuki et al., 2015), established the observed differences between the alternative methods and the standard method for clay fraction determination. In this regard, using clay proportion as an integrative criterion, the results presented in Figure 6 confirm that Bhm-sw and Rpm-md were significantly superior to the standard method and may therefore be considered the most suitable methods for textural analysis of soils from the region. These findings are particularly relevant considering that Bhm, although widely used as a standard method in national laboratories, has important limitations for taxonomic and pedogenetic purposes due to its imprecision in estimating fine fractions.

The correlation analysis in Figure 7 reveals that the four particle-size determination methods (Bhm, Bhm-sw, Rpm, and Rpm-md) are highly mutually consistent, exhibiting very strong positive correlations with each other (r = 0.94 to 0.99), which indicates that procedural modifications like sand weighting or dispersant mixtures do not significantly alter the relative textural characterization of these specific soils. When related to soil physicochemical properties, all four methods demonstrate a strong positive association with effective cation exchange capacity (CECe) (r = 0.61 to 0.74) and a pronounced negative correlation with OM (r = -0.65 to -0.46). This suggests that the mineral matrix primarily drives the variance captured by these methods; as the relative proportion of fine mineral particles increases, CECe rises while OM content decreases, potentially because the mineral fraction dilutes organic matter in these samples. Conversely, the methods show weak or negligible relationships with exchangeable bases (Ca^{2+}, Mg^{2+}), soil pH, and total CEC (CECt), alongside slight negative trends with Na^{+} and aluminum saturation (Al sat).

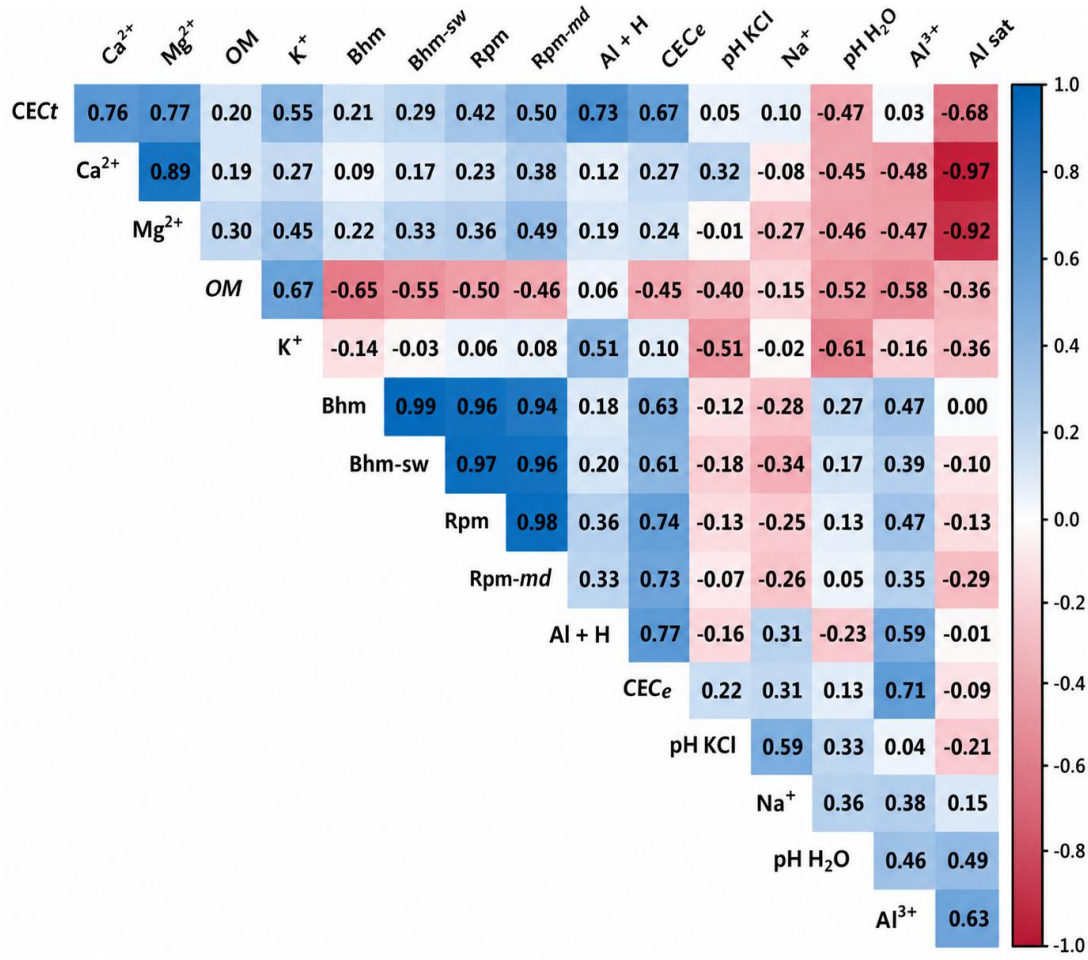


Figure 7. Pearson correlation matrix (n = 12) between the four particle-size analysis methods and soil physicochemical properties. The color scale indicates the direction and strength of the correlation (blue = positive; red = negative). Abbreviations: Bhm, Bouyoucos hydrometer method; Bhm-sw, Bouyoucos hydrometer method with sand weight; Rpm, Robinson pipette method; Rpm-md, Robinson pipette method with a mixture of dispersants; OM, organic matter; CECe, effective cation exchange capacity; CECt, total cation exchange capacity; Al+H, exchangeable acidity; Al sat, aluminum saturation.

Ultimately, this confirms that despite minor procedural variations, all four methods effectively capture the same underlying textural gradient, which is fundamentally linked to the soil mineral exchange complex (CECe) and inversely related to OM content.

The Principal Component Analysis (PCA) showed in Figure 8, which explained 65.5% of the total variance (Dim1 = 36.3%, Dim2 = 29.2%), revealed a tight clustering of the four textural methods (Bhm, Bhm-sw, Rpm, and Rpm-md), demonstrating that they are highly consistent and interchangeable for characterizing these soils, as procedural modifications like sand weight or dispersant mixtures did not fundamentally alter the multivariate structure. This textural variation was driven largely by soil acidity and aluminum dynamics; the method vectors were strongly positively associated with exchangeable acidity (Al+H) and effective CEC (CECe) but strongly negatively correlated with soil pH, sodium (Na^+), and aluminum saturation (Al sat). This suggests the methods capture the chemical gradients of highly weathered, leached tropical soils, where fine mineral fractions (clay and silt) provide negatively charged surfaces that retain H^+ and Al^{3+}. Conversely, the orthogonal positions of total CEC (CECt), K+, and OM indicate that textural variance is driven primarily by the mineral matrix rather than organic fractions, confirming that the evaluated methods provide a robust, comparable representation of the underlying physical and chemical variability in these acidic environments.

4. Conclusions

While the evaluated methods consistently show the same textural gradient, influenced by the mineral matrix, effective cation exchange capacity, and aluminum, they differ in their efficiency in determining the clay fraction. The standard Bouyoucos hydrometer method tends to underestimate the clay fraction in acidic soils because dispersion is incomplete. Given this limitation, the Bouyoucos hydrometer method, when combined with the weight of the sand fraction, and the pipette method using a mixture of dispersants proved statistically superior by quantifying a higher proportion of clay; they are therefore considered more accurate and reliable for routine textural analysis.

Author contributions

P. Y. Barraza-Macuri: Conceptualization, investigation, writing. **P. Lama-Isminio:** Investigation, writing, review, and editing. **D. A. Lama-Isminio:** Chemical analyses, writing, review, and editing. **J. A. Chia-Wong:** Statistical analysis. **B. P. Mezarino-Rengifo:** Review and editing. **M. J. Muñoz-Lino:** Review and editing.

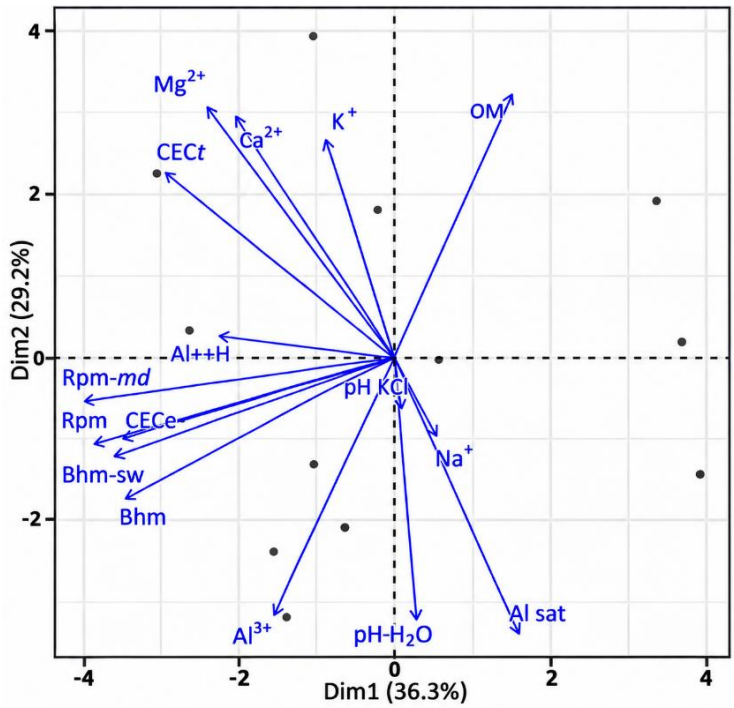


Figure 8. Principal Component Analysis (PCA) biplot of the four particle-size determination methods and soil physicochemical properties (n = 12). Black dots represent individual soil samples, and blue arrows indicate the variable loadings. Dim1 and Dim2 explain 36.3% and 29.2% of the total variance, respectively. Abbreviations: Bhm, Bouyoucos hydrometer method; Bhm-sw, Bouyoucos hydrometer method with sand weight; Rpm, Robinson pipette method; Rpm-md, Robinson pipette method with a mixture of dispersants; OM, organic matter; CECe, effective cation exchange capacity; CECt, total cation exchange capacity; Al+H, exchangeable acidity; Al sat, aluminum saturation.

Declaration of Competing Interest

The authors declare that they have no conflict of interest that could have influenced the work presented in this article.

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References

Acevedo, S. E., Contreras, C. P., Ávila, C. J., & Bonilla, C. A. (2021). Testing the integral suspension pressure method for soil particle size analysis across a range of soil organic matter contents. *International Agrophysics*, *35*(4), 357–363. https://doi.org/10.31545/INTAGR/144387

Alves, M. V., Delazeri, P., Nunes Nesi, C., & Ramos, M. R. (2018). Times of agitation and concentration of NaOH to characterize the soil texture. *Revista Agri-Environmental Sciences*, *4*(2), 34-40. https://doi.org/10.36725/agries.v4i2.907

Ashworth, J., Keyes, D., Kirk, R., & Lessard, R. (2001). Standard procedure in the hydrometer method for particle size analysis. *Communications in Soil Science and Plant Analysis*, *32*(5–6), 633–642. https://doi.org/10.1081/CSS-100103897

Beretta, A. N., Silbermann, A. V., Paladino, L., Torres, D., Bassahun, D., Musselli, R., & García-Lamohte, A. (2014). Soil textura analyses using a hydrometer: modification of the Bouyoucos method. *Ciencia e Investigacion Agraria*, *41*(2), 263–271. https://doi.org/10.4067/S0718-16202014000200013

Borja, M. K., Mercado, L. J., & Combatt, C. E. M. (2015). Chemical dispersants and quantification textural fractions by Bouyoucos and pipette methods. *Acta Agronómica*, *64*(4). https://doi.org/10.15446/acag.v64n4.45722

Callesen, I., Palviainen, M., Armolaitis, K., Rasmussen, C., & Kjønaas, O. J. (2023). Soil texture analysis by laser diffraction and sedimentation and sieving–method and instrument comparison with a focus on Nordic and Baltic forest soils. *Frontiers in Forests and Global Change*, *6*. https://doi.org/10.3389/ffgc.2023.1144845

Callesen, L., Liski, J., Raulund-Rasmussen, K., Olsson, M. T., Tau-Strand, L., Vesterdal, L., & Westman, C. J. (2003). soil carbon stores in Nordic well-drained forest soil-relationships with climate and texture class. *Global Change Biology*, *9*, 358–370.

Camargo, O. A. de, Moniz, A. C., Jorge, J. A., & Valadares, J. M. A. S. (2009). *Métodos de análise química, mineralógica e física de solos do Instituto Agronômico de Campinas*. Instituto Agronômico, Boletim Técnico, 106, 77 p. Campinas, Brasil.

Chittleborough, D. J., Walker, P. H., & Oades, J. M. (1984). Textural differentiation in chronosequences from esatern Australia, II. Evidence from particle-size distributions. *Geoderma*, *32*, 203–226.

Combatt-Caballero, E. M., Palencia-L, M., & Borja-M, K. (2018). Particle size distribution by Bouyoucos in slightly alkaline soils from department of Cordoba, Colombia. *Acta Agronomica*, *67*(1). https://doi.org/10.15446/acag.v67n1.60762

Corá, J. E., Fernandes, C., Beraldo, J. M. G., & Marcelo, A. V. (2009). Adição de areia para dispersão de solos na análise granulométrica. *R. Bras. Ci. Solo*, *33*, 255–262.

Cunha, J. C., Freire, M. B. G. dos S., Ruiz, H. A., Fernandes, R. B. A., & Alvarez V., V. H. (2014). Comparação de dispersantes químicos na análise granulométrica de solos do Estado de Pernambuco. *Revista Brasileira de Engenharia Agricola e Ambiental*, *18*(8), 783–789. https://doi.org/10.1590/1807-1929/agriambi.v18n08p783-789

Curcio, D., Ciraolo, G., D'Asaro, F., & Minacapilli, M. (2013). Prediction of Soil Texture Distributions Using VNIR-SWIR Reflectance Spectroscopy. *Procedia Environmental Sciences*, *19*, 494–503. https://doi.org/10.1016/j.proenv.2013.06.056

De Souza, E. S., Fernandes, A. R., De Souza Braz, A. M., De Oliveira, F. J., Alleoni, L. R. F., & Campos, M. C. C. (2018). Physical, chemical, and mineralogical attributes of a representative group of soils from the eastern Amazon region in Brazil. *Soil*, *4*(3), 195–212. https://doi.org/10.5194/soil-4-195-2018

Donagemma, G. K., Ruiz, H. A., Alvarez V., V. H., Ker, J. C., & Fontes, M. P. F. (2008). Fósforo remanescente em argila e silte retirados de Latossolos após pré-tratamentos na análise textural. *Revista Brasileira de Ciencia Do Solo*, *32*(4), 1785–1791. https://doi.org/10.1590/s0100-06832008000400043

Empresa Brasileira de Pesquisa Agropecuaria - EMBRAPA. (2017). Análise granulométrica (Parte I - Análises Físicas). Manual de Métodos de Análise de Solo (Portuguese), 573 p.

Faé, G. S., Montes, F., Bazilevskaya, E., Añó, R. M., & Kemanian, A. R. (2019). Making soil particle size analysis by laser diffraction compatible with standard soil texture determination methods. *Soil Science Society of America Journal*, *83*(4), 1244–1252. https://doi.org/10.2136/sssaj2018.10.0385

Fisher, P., Aumann, C., Chia, K., O'Halloran, N., & Chandra, S. (2017). Adequacy of laser diffraction for soil particle size analysis. *PLoS ONE*, *12*(5). https://doi.org/10.1371/journal.pone.0176510

García, J., Medina, H., & Núñez, D. (2008). El método del hidrómetro: influencia de los tiempos de lecturas en el cálculo de la distribución del tamaño de partículas en suelos de la Habana. *Cultivos Tropicales*, *29*(2), 21–26.

Gee, G. W., & Bauder, J. W. (1979). Particle size analysis by hydrometer: a simplified method for routine textural analysis and a aensitivity test of measurement parameters. *Soil Sci. Soc. Am. J.*, *43*, 1004–1007.

Jensen, J. L., Schjønning, P., Watts, C. W., Christensen, B. T., & Munkholm, L. J. (2017). Soil texture analysis revisited: Removal of organic matter matters more than ever. *PLoS ONE*, *12*(5). https://doi.org/10.1371/journal.pone.0178039

Júnior, A. L. N. do, Souza, L. S. da, Silva, E. O. da, Silva, F. T. S. dos, Santos, N. A. C., et al. (2014). Concentrações de dispersantes químicos e tempos de contato na dispersão de solos representativos do estado da Bahia. *Magistra, Cruz Das Almas*, *26*(1), 68–74.

Kalra, Y. P., & Maynard, D. G. (1991). *Methods manual for forest soil and plant analysis*. Forestry Canada, Northwest Region, Northern Forestry Centre.

Kraemer, F. B., Fernández, P. L., Ceddia, M. B., Chagas, C. I., & Morrás, H. M. J. (2016). Efectividad de distintos pretratamientos en el análisis granulométrico de tres suelos contrastantes de la región pampeana. *Ciencia del Suelo*, *34*(1), 163–172.

Martínez, V. W., Valdivia, F. E. J., & Cuyubamba, P. V. (1998). *Geología de los cuadrángulos de Aucayacu, río Santa Ana y Tingo María. Hojas 18-K, 18-I y 19-K* (Primera Edición).

Mauri, J., Ruiz, H. A., Fernandes, R. B. A., Ker, J. C., & Rezende, L. R. M. (2011). Dispersantes químicos na análise granulométrica de Latossolos. *Rev. Bras. Ciênc. Solo*, *35*(4), 1577-1284. https://doi.org/10.1590/S0100-06832011000400021

Messing, I., Mingot Soriano, A. M., Nimblad Svensson, D., & Barron, J. (2024). Variability and compatibility in determining soil particle size distribution by sieving, sedimentation and laser diffraction methods. *Soil and Tillage Research*, *238*, Art. 105987. https://doi.org/10.1016/j.still.2023.105987

Mozaffari, H., Moosavi, A. A., Baghernejad, M., & Cornelis, W. (2024). Revisiting soil texture analysis: Introducing a rapid single-reading hydrometer approach. *Measurement*, *228*. Art. 114330. https://doi.org/10.1016/j.measurement.2024.114330

Mwendwa, S. (2022). Revisiting soil texture analysis: Practices towards a more accurate Bouyoucos method. *Heliyon*, *8*(5). https://doi.org/10.1016/j.heliyon.2022.e09395

Oliveira, G. C. de, Júnior, M. S. D. de, Vitorino, A. C. T., Ferrerira, M. M., de Sá, M. A. C., & Lima, J. M. (2002). Agitador

horizontal de movimento helicoidal na dispersão mecânica de amostras de três Latossolos do sul e campos das vertentes de Minas Gerais. *Ciênc. Agrotec.*, *26*, 881–887.

Owji, A., Esfandiarpour Boroujeni, I., Kamali, A., Hosseinifard, S. J., & Bagheri Bodaghabadi, M. (2014). The effects of hydrometer reading times on the spatial variability of soil textures in southeast Iran. *Arabian Journal of Geosciences*, *7*(4), 1491–1499. https://doi.org/10.1007/s12517-012-0786-0

Pal, D. K. (2021). *Clay and other minerals in the formation, management and ecosystem services of Indian tropical soils*. The Clay Minerals Society of India - CMSI, 72 p. New Delhi, India.

Papuga, K., Kaszubkiewicz, J., Wilczewski, W., Stas, M., Belowski, J., & Kawałko, D. (2018). Soil grain size analysis by the dynamometer method - A comparison to the pipette and hydrometer method. *Soil Science Annual*, *69*(1), 17–27. https://doi.org/10.2478/ssa-2018-0003

Quesada, C. A., Lloyd, J., Schwarz, M., Patiño, S., Baker, T. R., et al. (2010). Variations in chemical and physical properties of Amazon forest soils in relation to their genesis. *Biogeosciences*, *7*(5), 1515–1541. https://doi.org/10.5194/bg-7-1515-2010

Rodrigues, C., Oliveira, V. A. de, Silveira, P. M. da, & Santos, G. G. (2011). Chemical dispersants and pre-tratament to determine clay in soils with different mineralogy. *R. Bras. Ci. Solo*, *35*(5), 1589–1596. https://doi.org/10.1590/S0100-06832011000500013

Rodríguez, R., Eber, M., Tintaya, C., Sánchez, E., David, C., Farfan, O., Fabian, C., Edwin, Q., & Saldivar, G. (2017). *Geología del cuadrángulo de Rioja, Hoja 13i*. INGEMMET, Boletín, Serie A: Carta Geológica Nacional, 150, 82 p., 4 mapas (Escala 1:50 000).

Ruiz, H.A. (2003). Física do solo. Universidade Federal de Viçosa. 64 p. Brasil.

Ruiz, H. A. (2005). Incremento da exãtidao da análise granulométrica do solo por meio da coleta da suspensão (silte + argila). *R. Bras. Ci. Solo*, *29*, 297–300.

Schlindwein, J. A., Antonio, A., Ii, M., & Fioreli-Perira, E. C. (2011). Adjustment of the expedite method for clay content determination in Rondônia soils. *Ciência Rural*, *41*, 2096–2100.

Suzuki, L. E. A. S., Reichert, J. M., Albuquerque, J. A., Reinert, D. J., & Kaiser, D. R. (2015). Dispersion and flocculation of Vertisols, Alfisols and Oxisols in southern Brazil. *Geoderma Regional*, *5*, 64–70. https://doi.org/10.1016/j.geodrs.2015.03.005

Tavares-Filho, J., & Magalhães, F. S. de. (2008). Dispersão de amostras de Latossolo Vermelho Eutroférrico influenciadas por pré-tratamento para oxidacão da matéria orgânica e pelo tipo de agitacão mecânica. *R. Bras. Ci. Solo*, *32*, 1429–1435.

Walkley, A., Black, I.A. (1934). An examination of the degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science*, *37*, 29-38. https://doi.org/10.1097/00010694-193401000-00003

Zimmermann, I., & Horn, R. (2020). Impact of sample pretreatment on the results of texture analysis in different soils. *Geoderma*, *371*, Article 114379. https://doi.org/10.1016/j.geoderma.2020.114379