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Exchangeable cations determined by different methods: Implications for soil classification and evaluation

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ABSTRACT: For a comprehensive and global evaluation of soils, it is essential to define common diagnostic properties among classification or interpretative systems. Specifically, in soil taxonomy, the Brazilian Soil Classification System (SiBCS) adopts analytical methods that differ from those used in international systems such as the World Reference Base for Soil Resources (WRB) and the Soil Taxonomy (ST). In the chemical properties, differences are observed in the determination of exchangeable basic cations and potential acidity (H+Al), as well as derived properties such as the sum of bases (SB), cation exchange capacity (CEC_{pH7}), and base saturation (V). This study aimed to: (i) to compare the values of H+Al, SB, CEC, and V in Brazilian soils determined by different analytical methods; (ii) to propose regression models to harmonize values of the properties obtained through different analytical procedures; and (iii) to compare the threshold values of diagnostic properties used as classification criteria in the SiBCS with those adopted by WRB and ST. A representative database of Brazilian soils published in the Brazilian Soil Data Repository (SoilData) was used, comprising 2,217 samples from surface horizons and 3,726 from subsurface horizons. Values of SB, CEC, and V for surface and subsurface horizons, obtained using the methods applied in the SiBCS, were lower than those determined by the WRB and ST methods. The difference in the estimated V values was below 5 %, which falls within the analytical error range. Thus, the SiBCS criteria of V ≥50 % for identifying eutrophic character and >65 % for defining a chernozemic A horizon were found to be high, and they tend to underestimate several Brazilian soil classes, particularly those classified as *Chernossolos*, as well as the misclassification of anthropic and other soils modified by agricultural practices. It is proposed that the SiBCS adopt thresholds similar to those used in WRB and ST for base saturation, or alternatively, apply regression equations to improve correspondence among the systems.

Keywords: analytical methods, diagnostic properties, soil classification, data harmonization.

INTRODUCTION

Defining compatible soil diagnostic properties across taxonomic and interpretative systems is essential for coherent classification and global correlation. Among the chemical properties related to nutrient availability and soil acidity, either inherent or induced by management practices, exchangeable basic cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}) are particularly important, along with potential acidity (H+Al) and active acidity (Al^{3+}) (Tomé Jr., 1997).

In addition to their absolute concentrations, exchangeable cations are used to calculate properties that represent the expression of negatively charged sites of soil particles, including the sum of bases (SB), cation exchange capacity (CEC), and effective cation exchange capacity (CEC_e), as well as the relative concentration of cations expressed as base saturation (V). These soil properties define diagnostic criteria for distinguishing soil horizons and classes within the Brazilian Soil Classification System (Santos et al., 2025) and the international systems World Reference Base for Soil Resources (WRB) (IUSS Working Group, 2022) and Soil Taxonomy (ST) (Soil Survey Staff, 2022). They are also widely employed in soil fertility assessment and in liming recommendations (Tomé Jr., 1997).

Regarding the determination of these properties, although the different soil classification systems employ a similar set of chemical properties to establish their taxonomic criteria, they adopt distinct analytical methods. In the SiBCS, calcium (Ca^{2+}), magnesium (Mg^{2+}), and aluminum (Al^{3+}) are extracted using a potassium chloride (KCl) solution, whereas sodium (Na^{+}) and potassium (K^{+}) are extracted using a mixture of hydrochloric acid and sulfuric acid (Mehlich-1). Potential acidity (H+Al) is extracted using a calcium acetate [$Ca(OAc)_2$] solution buffered at pH 7.0. Cation exchange capacity CEC_{pH7} is obtained indirectly by summing the SB and H+Al values (Teixeira et al., 2017).

In contrast, the WRB and ST systems use an ammonium acetate (NH_4OAc) solution buffered at pH 7 to extract the basic cations and to determine the potential cation exchange capacity directly of the CEC_{pH7} (CEC_{NH_4OAc}). Additionally, for saline and alkaline soils, the $CEC_{pH8.2}$ is determined as the sum of SB_{NH_4OAc} and H+Al extracted with a barium chloride ($H+Al_{BaCl_2}$) solution buffered at pH 8.2 (IUSS Working Group WRB, 2022; Soil Survey Staff, 2014). In all three classification systems, V is calculated as the ratio between SB and CEC_{pH7}, and in specific cases in the WRB and ST, as the ratio between SB and $CEC_{pH8.2}$.

Given these analytical differences, some studies have evaluated methods used to determine absolute and relative contents of exchangeable cations and examined the correspondence among values derived from these analytical procedures for Brazilian soils (Verdade, 1956; van Raij and Küpper, 1966; Castro et al., 1972; Oliveira, 1975; Camargo et al., 1982). The first Brazilian initiative to assess the consistency of interpretations and concepts across different soil classification systems took place during the First International Soil Classification Workshop (1st ISCW) (Camargo and Beinroth, 1978). Soil horizon samples from four *Podzólico Vermelho-Amarelo* (currently *Argissolo Vermelho-Amarelo*) (Acrisol or Lixisol – WRB) and one *Terra Roxa Estruturada* (currently *Nitossolo*) (Nitisol – WRB) profile were analyzed, and conversion equations were proposed to relate the values of exchangeable bases, acidity, CEC, and V obtained using SiBCS methods to those determined by the international procedures (Ikawa, 1978). Later, Larach and Paolinelli (1982) compiled previous results, including those from the International Committee on Low Activity Clays (ICOMLAC) (Moormann, 1985), and suggested that a V value of 50 % obtained using ST methods would correspond to a V value of 65 % using SiBCS methods. According to the authors, in surface horizons, a V value of 50 % determined by ST would be equivalent to 58 % in SiBCS.

In 1999, the first edition of the SiBCS (Embrapa, 1999), following the suggestion of Larach and Paolinelli (1982), the V thresholds of 50 % was adopted to distinguish eutrophic and dystrophic materials, and V equal or higher than 65 % to define the chernozemic A horizon in relation to other A horizons (A prominent and A humic), a criterion maintained in the current edition (Santos et al., 2025). These thresholds are roughly equivalent to the 35 and 50 % limits, adopted in ST and WRB, respectively. However, the estimated 15 % difference becomes evident only when considering the V based on $CEC_{pH8.2}$, which is not used as a diagnostic criterion for surface horizons in the international systems. This suggests that the SiBCS applies more restrictive criteria than the ST and WRB. Moreover, the proposal by Larach and Paolinelli (1982) was based on a small, unrepresentative sample, with limited spatial and thematic representation across Brazilian territory.

Given the differences in extractants used in laboratory analyses, it is necessary to establish equivalence or harmonization criteria between diagnostic properties values obtained by the SiBCS and those determined in international systems, particularly for SB, CEC, and V values. This study hypothesizes that reevaluating the correspondence between SB, CEC (referred to as CTC in the SiBCS), and V values obtained by different analytical methods will improve diagnostic criteria within the SiBCS, while allowing to represent better soils with high natural fertility or significant anthropic modifications, and finally enhance consistency with the criteria used in WRB and ST.

The specific objectives of this study were: (i) to compare H+Al, SB, CEC, and V values of Brazilian soils determined using different analytical methods; (ii) to propose regression models to harmonize values of properties obtained through different analytical methods; and (iii) to compare the threshold values of diagnostic properties used as classification criteria in the SiBCS with those adopted by WRB and ST.

MATERIALS AND METHODS

Soil data

The data used in this study were compiled from publications covering soils of the entire Brazilian territory. Among these sources are the proceedings of the 1st International Soil Classification Workshop (1st ISCW) (Camargo and Beinroth, 1978), which include soil samples from the states of Rio de Janeiro, Paraná, Alagoas, and Pernambuco, and the 8th ISCW (Camargo et al., 1986), comprising samples from Rio de Janeiro, São Paulo, Minas Gerais, Goiás, and Distrito Federal. Twenty-one reports from the RadamBrasil Project (1970 - 1985) were included, providing spatial coverage across 20 Brazilian States: Santa Catarina, Rio Grande do Sul, Paraná, Amazonas, Acre, Mato Grosso, Rondônia, Roraima, Goiás, Pará, Piauí, Tocantins, Pernambuco, Paraíba, Ceará, Bahia, Mato Grosso do Sul, Minas Gerais, São Paulo, Espírito Santo, and the Federal District.

Documents or datasets not available in digital format were tabulated and digitized. All original reports and datasets, as well as the final database used in this study, are described and made available through the Brazilian Soil Data Repository (SoilData - soildata.mapbiomas.org) and the details of the sources are in table 1.

Soil samples in these reports were analyzed in paired format using both the analytical methodologies adopted by the SiBCS and those used in the international classification systems WRB and ST. The RadamBrasil Project data were generated at the former laboratory of the Superintendency for the Development of the Southern Region (SUDESUL) in Pelotas, Rio Grande do Sul State, Brazil. Data from the 1st and 8th ISCW were generated by the laboratory of the former National Service for Soil Survey and Classification in Rio de Janeiro, Brazil, and by the National Soil Survey Laboratory of the Soil Conservation Service in Lincoln, Nebraska, USA. The analytical methodologies used to determine the chemical properties included H+Al, SB, CEC_{pH7}, $CEC_{pH8.2}$, and V (Table 2).

Table 1. Bibliographic sources, number of profiles and horizons compiled in the soil database

Citation	Number of profiles	Number of horizons	DOI (SoilData)
Camargo MN, Beinroth FH. Proceeding of first international soil classification workshop. Rio de Janeiro: Embrapa-SNLCS; 1978.	6	26	https://doi.org/10.60502/SoilData/76VTJW
Beinroth FH, Camargo MN, Kimble JM, Beinroth FH, Arango HP. Proceeding of the 8th international soil classification workshop. Part 2: Field trip background site and pedon descriptions analytical data. Rio de Janeiro: Embrapa-SNLCS, USDA-SMSS, University of Puerto Rico; 1988.	23	156	https://doi.org/10.60502/SoilData/BAGI6F
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SG.22 Curitiba, parte da folha SG.21 Assunção e folha SG.23 Iguape: Geologia, geomorfologia, pedologia, vegetação, uso potencial da terra. Rio de Janeiro: IBGE; 2018.	70	325	https://doi.org/10.60502/SoilData/ONP08P
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SB 19 Juruá: Geologia, geomorfologia, pedologia, vegetação e potencial de uso da terra. Rio de Janeiro: Departamento Nacional da Produção Mineral; 1977. (Levantamento de Recursos Naturais, 15).	42	201	https://doi.org/10.60502/SoilData/0QIONA
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folhas SB/SC.18 Javari/Contamana: Geologia, geomorfologia, pedologia, vegetação e potencial de uso da terra. Rio de Janeiro: Departamento Nacional da Produção Mineral; 1977. (Levantamento de Recursos Naturais, 13).	18	99	https://doi.org/10.60502/SoilData/OSBG2D
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SC.20 Porto Velho: Geologia, geomorfologia, pedologia, vegetação e potencial de uso da terra. Rio de Janeiro: Departamento Nacional da Produção Mineral; 1978. (Levantamento de Recursos Naturais, 16).	37	181	https://doi.org/10.60502/SoilData/IQ8VPI
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SB.20 Purus: Geologia, geomorfologia, pedologia, vegetação e potencial de uso da terra. Rio de Janeiro: Departamento Nacional da Produção Mineral; 1978. (Levantamento de Recursos Naturais, 17).	50	216	https://doi.org/10.60502/SoilData/ISZ6YW
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SA.20 Manaus: Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro: Departamento Nacional da Produção Mineral; 1978. (Levantamento de Recursos Naturais, 18).	74	366	https://doi.org/10.60502/SoilData/YTMMEF
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SD.20 Guaporé: Geologia, geomorfologia, pedologia, vegetação: Uso potencial da terra. Rio de Janeiro: Departamento Nacional da Produção Mineral; 1979. (Levantamento de Recursos Naturais, 19).	64	320	https://doi.org/10.60502/SoilData/CU99IP
Brasil. Ministério das Minas e Energia.. Projeto RadamBrasil. Folha SC.21. Juruena: Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro: Departamento Nacional da Produção Mineral; 1980. (Levantamento de Recursos Naturais, 20).	123	603	https://doi.org/10.60502/SoilData/56JRIF
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SA.24 Fortaleza: Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro: Secretaria-Geral; 1981. (Levantamento de Recursos Naturais, 21).	16	43	https://doi.org/10.60502/SoilData/Y9ERKO

Continue

Continuation

Citation	Number of profiles	Number of horizons	DOI (SoilData)
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil Folha SC.22 Tocantins:Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro: Secretaria-Geral; 1981. (Levantamento de Recursos Naturais, 22).	168	851	https://doi.org/10.60502/SoilData/NN96QP
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folhas SB. 24/25 Jaguaribe/Natal: Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro: Secretaria-Geral; 1981. (Levantamento de Recursos Naturais, 23).	12	31	https://doi.org/10.60502/SoilData/SE1JMZ
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil Folha SD. 24 Salvador: Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro: Secretaria-Geral; 1981. (Levantamento de Recursos Naturais, 24).	25	39	https://doi.org/10.60502/SoilData/PT0SSQ
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SD.22 Goiás: Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro: Secretaria-Geral; 1981. (Levantamento de Recursos Naturais, 25).	177	790	https://doi.org/10.60502/SoilData/QOJKKZ
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SD.21 Cuiabá: Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro: Secretaria-Geral; 1982. (Levantamento de Recursos Naturais, 26).	111	556	https://doi.org/10.60502/SoilData/01IXMH
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SE.21 Corumbá e parte da Folha SE.20: Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro: Secretaria-Geral; 1982. (Levantamento de Recursos Naturais, 27).	17	83	https://doi.org/10.60502/SoilData/BDJ2H2
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil Folha SF.21 Campo Grande: Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro: Secretaria-Geral; 1982. (Levantamento de Recursos Naturais, 28).	14	60	https://doi.org/10.60502/SoilData/LJ8JRO
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SD.23 Brasília: Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro: Secretaria-Geral; 1982. (Levantamento de Recursos Naturais, 29).	40	72	https://doi.org/10.60502/SoilData/E7Z9SS
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil Folhas SC.24/25 Aracaju/Recife: Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro: Secretaria-Geral; 1983. (Levantamento de Recursos Naturais, 30).	5	18	https://doi.org/10.60502/SoilData/HXQY0O
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SD.22 Goiás: Geologia, geomorfologia, pedologia, vegetação e potencial de uso da terra. Rio de Janeiro: Secretaria-Geral; 1983. (Levantamento de recursos naturais, 31).	157	720	https://doi.org/10.60502/SoilData/HLLKXP
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SH.22 Porto Alegre e parte das Folhas SH.21 Uruguaiana e SI.22 Lagoa Mirim: Geologia, geomorfologia, pedologia, vegetação, uso potencial da terra. Rio de Janeiro: IBGE; 1986. (Levantamento de recursos naturais, v. 33).	31	168	https://doi.org/10.60502/SoilData/9ZXJOG
Brasil. Ministério das Minas e Energia. Projeto RadamBrasil. Folha SE.24 Rio Doce: Geologia, geomorfologia, pedologia, vegetação, uso potencial da terra. Rio de Janeiro: IBGE; 1987. (Levantamento De Recursos Naturais, v. 34).	53	102	https://doi.org/10.60502/SoilData/6RDOKV
Sum	**1,304**	**6,026**	**-**

Table 2. Analytical methods used as diagnostic criteria in the Brazilian Soil Classification System (SiBCS) and in the international systems World Reference Base for Soil Resources (WRB) and Soil Taxonomy (ST)

Property	SiBCS	WRB e ST
Ca^{2+}, Mg^{2+} and Al^{3+}	Extracted by potassium chloride solution (1 mol L^{-1})	Al^{3+} - Extracted by potassium chloride solution (1 mol L^{-1})
K^+ and Na^+	Extracted by Mehlich-1 (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4)	-
$Ca^{2+}+Mg^{2+}+Na^++K^+$	-	Extracted by ammonium acetate (NH_4OAc) solution (1 mol L^{-1}) buffered at pH7
H^++Al^{3+} and $H+Al_{BaCl_2}$	Extracted by calcium acetate [$Ca(OAc)_2$] solution (0.5 mol L^{-1}) buffered at pH7	Extracted by barium chloride ($H+Al_{BaCl_2}$) solution (0.25 mol L^{-1}) buffered at pH8.2
SB and SB_{NH_4OAc}	$Ca^{2+} + Mg^{2+} + K^+ + Na$	$Ca^{2+} + Mg^{2+} + K^+ + Na$
CTC_{pH7} and CEC	SB + (H+Al)	Extracted by ammonium acetate (NH_4OAc) solution (1 mol L^{-1}) buffered at pH7
$CEC_{pH8.2}$	-	SB_{NH4OAc} + ($H+Al_{BaCl_2}$)
V and V_{pH7}	SB / CTC_{pH7} × 100	SB_{NH4OAc} / CEC_{pH7} × 100
$V_{pH8.2}$	-	SB_{NH4OAc} / $CEC_{pH8.2}$ × 100

SB: sum of bases in SiBCS; SB_{NH_4OAc}: sum of bases in WRB and ST; CTC_{pH7}: cation exchange capacity in SiBCS; CEC_{pH7}: cation exchange capacity in WRB and ST; $CEC_{pH8.2}$: cation exchange capacity in ST; V: base saturation in SiBCS; V_{pH7}: base saturation in WRB and ST; $V_{pH8.2}$: base saturation in ST.

Data processing

To ensure comparability across different datasets, all measurement units and nomenclature were standardized and verified. This process included identifying duplicate records, verifying values outside expected ranges, and correcting deviations in accordance with established soil composition patterns. Subsequently, the dataset was examined for consistency to identify possible input errors or discrepancies. This analysis involved assessing the dispersion of values obtained by each analytical method, with particular attention to data showing greater variability relative to the established trend line, and inspecting the minimum and maximum values.

When inconsistencies were observed, a cautious approach was adopted to preserve the integrity of the analytical results while preserving the authenticity of the original data sources. Although some inconsistencies might have resulted from transcription or typing errors, the original data was retained to ensure transparency. In cases where two or more inconsistencies were detected, the affected soil horizons were excluded from the dataset. This measure prevented distortions that could compromise the validity of subsequent analyses. When data were missing for one of the paired analytical methods, the corresponding observation was also excluded to ensure that all comparisons were based exclusively on complete paired data.

Statistical analysis

For each property determined by each analytical method, descriptive statistics (mean, median, standard deviation, minimum, and maximum) were calculated separately for surface (A horizon) and subsurface (B and C horizons).

Assumptions of residual normality were examined both graphically (Q–Q plots) and formally using the Shapiro–Wilk test. Homogeneity of variance was evaluated graphically (residuals versus predicted values) and through the Breusch–Pagan test. As expected for large datasets ($n > 2,000$), these tests indicated statistically significant deviations from both normality and homoscedasticity ($p<0.05$). However, given the sample size, a graphical assessment, which is more informative in such cases, was therefore prioritized. The Q–Q plots showed no severe departures from normality, and residual plots indicated only mild heteroscedasticity.

Mean values of results from each analyses were compared using the T-test for two samples with equal variances. Correlation among properties determined by different analytical methods was modeled using regression analysis. Values obtained from the SiBCS reference method were plotted on the x-axis, while those from international methods were plotted on the y-axis. The regression models were evaluated for goodness of fit, with particular attention paid to the coefficients of determination (R^2) and statistical significance.

RESULTS AND DISCUSSION

Database composition

Following consistency assessment, a total of 2,217 surface horizon samples and 3,726 subsurface horizon samples were retained for the analysis of exchangeable cations and potential acidity determined by different analytical methods. The dataset represents a wide range of textural classes, as shown in the ternary diagrams (Figure 1).

Evaluation of properties in surface horizons

The H+Al values determined by the SiBCS method were lower than those obtained using the $H+Al_{BaCl_2}$ method (WRB and ST). Similarly, the SiBCS-derived values of SB, CTC, and V were lower than the SB_{NH4OAc}, CEC_{pH7}, and V_{pH7}, respectively (Table 3). As a result, when the CTC (SiBCS) was lower than the $CEC_{pH8.2}$ (WRB and ST), the corresponding V value was higher than the $V_{pH8.2}$ (Table 3).

The differences between SB and H+Al directly influence the base saturation, as previously noted by Larach and Paolinelli (1982). According to these authors, determination of CEC in Brazilian soils using the analytical methods currently adopted by SiBCS resulted in lower values than those obtained using the international methods. They proposed that "for operational purposes, a V value of 65 % obtained from the former SNLCS (currently Embrapa Solos) would correspond to 50 % in the Soil Conservation Service (SCS, pH 7)."

Since the first edition of the SiBCS (Embrapa, 1999), this assumption has been adopted, establishing 65 % as the minimum V threshold for defining the chernozemic A horizon. This threshold remains in the current 2025 edition (Santos et al., 2025). However, this criterion was originally based on only 28 samples from four *Argissolos* (Acrisol or Lixisol - WRB) and one *Nitossolo* (Nitisol - WRB) profile, providing limited representativeness of Brazilian soils. Moreover, the 65 % threshold was not supported by quantitative correspondence analyses but was merely suggested as a practical approximation.

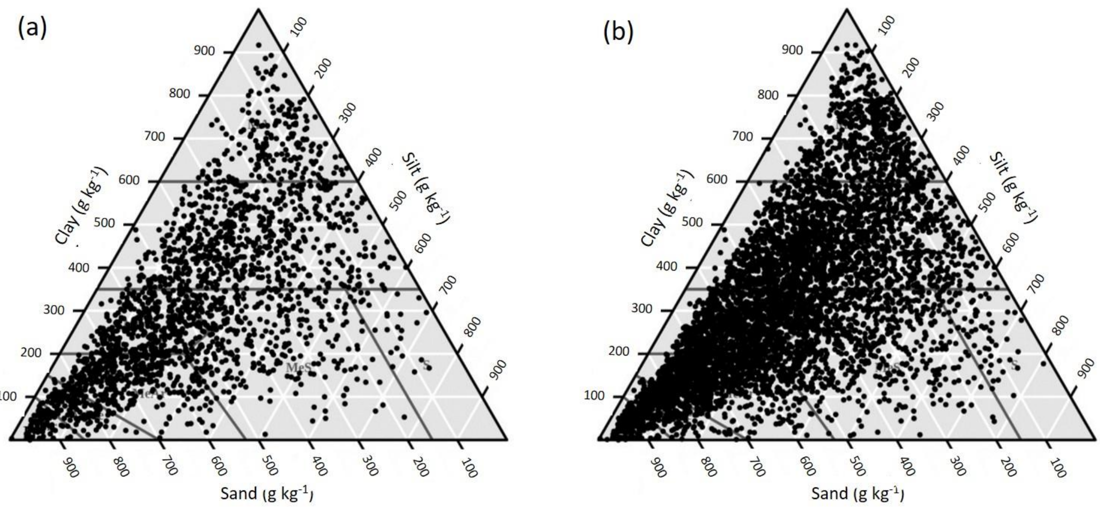

Figure 1. Distribution of horizons according to particle-size fractions in ternary diagrams. (a) Surface horizons (A and transitional horizons), n = 2,217; (b) Subsurface horizons (E, B, C, and transitional horizons), n = 3,726.

Table 3. Values of properties for surface horizons, calculated from exchangeable cations and potential acidity determinations obtained using the SiBCS, WRB and ST methods

Statistic	SiBCS				WRB and ST					
	H+Al	SB	CTC_{pH7}	V	$H+Al_{BaCl_2}$	SB_{NH_4OAc}	CEC_{pH7}	$CEC_{pH8.2}$	V_{pH7}	$V_{pH8.2}$
	$cmol_c\ kg^{-1}$			%	$cmol_c\ kg^{-1}$				%	
Average	5.41 B	2.25 B	7.32 Bb	27 Ba	9.54 A	2.81 A	7.86 A	11.75a	30 A	20b
Median	4.22	0.71	5.80	16	7.83	0.88	6.10	9.68	19	12
Stand. Dev.	4.51	3.99	5.61	26	6.35	4.97	6.23	8.11	27	20
Minimum	0.00	0.00	0.15	0	0.00	0.02	0.31	0.31	0	0
Maximum	37.62	36.63	43.88	100	47.83	46.65	50.30	62.26	100	100
Count	**2,159**	**1,693**	**1,690**	**1690**	**2,159**	**1,693**	**1,690**	**1,690**	**1,690**	**1,690**

Stand Dev: standard deviation; SB: sum of bases in SiBCS; SB_{NH_4OAc}: sum of bases in WRB and ST; CTC_{pH7}: cation exchange capacity in SiBCS; CEC_{pH7}: cation exchange capacity in WRB and ST; $CEC_{pH8.2}$: cation exchange capacity in ST; V: base saturation in SiBCS; V_{pH7}: base saturation in WRB and ST; $V_{pH8.2}$: base saturation in ST. Similar letters do not differ from each other when obtained by different methods according to the T-test at $p<0.05$.

The adoption of V 65 % as the criterion for identifying a *Chernozêmico* A horizon constitutes a relatively stringent standard, which likely leads to an underestimation of these diagnostic horizons and, consequently, of the soil classes in which they occur, particularly the order *Chernossolos* (Santos et al., 2025) (Chernozems, Kantanozems, or Phaeozems, WRB). These soils, and others with *Chernozêmico* A horizons, are typically associated with higher natural fertility.

In agricultural soils, the eutrophic character of a soil is generally interpreted as higher fertility, and management practices often aim to increase the exchangeable Ca, Mg, and V levels (Tomé Jr., 1997), especially in dystrophic soils as defined by the SiBCS criteria (Santos et al., 2025). These properties are also used to interpret land-use potential in various international systems, such as discussed within the International Network of Black Soils (FAO/ITPS, 2015), where the black soils are recognized as highly productive soils and one of the categories is defined by CEC_{pH7} ≥25.0 $cmol_c\ kg^{-1}$ and V ≥50 %.

Accordingly, correspondence among SiBCS and international analytical methods for H+Al, SB, CEC, and V was assessed through linear regression models (Figures 2, 3, 4, 5, 6, and 7). The resulting predictive equations are presented in table 5.

Properties of subsurface horizons

The exchangeable cation and potential acidity values obtained using the analytical method adopted by the SiBCS were lower than those determined by the methods used in international systems (WRB and ST) (Table 4). The same trend was observed for CTC, whose value is lower than that of $CEC_{pH8.2}$, and consequently, the V is higher than $V_{pH8.2}$ (Table 4).

The most appropriate way to establish correspondence among properties values determined by different methods is through linear regression analysis. These functions were derived from relationships between the parameters H+Al, SB, CTC, and V obtained by the SiBCS method, and those obtained by $H+Al_{BaCl_2}$, SB_{NH_4OAc}, CEC_{pH7}, $CEC_{pH8.2}$, V_{pH7}, and $V_{pH8.2}$ (Figures 2, 3, 4, 5, 6, and 7). The regression equations for defining these correspondences are presented in table 6.

Equations for obtaining correspondence among methods

Notably, due to differences in the extractants used in laboratory analyses for determining exchangeable cation contents and soil potential acidity, it is necessary to adjust or harmonize property values obtained through the SiBCS method with those obtained by WRB and ST. This adjustment is particularly important for CEC and V, which are key parameters in defining diagnostic properties, diagnostic horizons, and soil classes across multiple hierarchical levels.

To establish correspondence among property values, predictive equations were proposed for surface horizons (Table 5) and subsurface horizons (Table 6). In these tables, the first column refers to the property to be estimated based on its value determined by the other method (included in the equation).

Regarding the methodological differences, it is important to note that for H+Al, the $BaCl_2$ solution used in the ST and WRB methods tends to overestimate values compared to those obtained with the 0.5 mol L^{-1} $Ca(OAc)_2$ (pH 7.0) solution in the method preconized by SiBCS. The $BaCl_2$ solution extracts cations adsorbed to both permanent and pH-dependent charges. For basic cations (Ca^{2+} and Mg^{2+}), the ion-exchange principle is similar among the different extractant solutions, whereas both methods used the same KCl solution for Al^{3+}. As for Na^+ and K^+, ion exchange is performed in the ST and WRB systems, whereas in the SiBCS, a dilute strong acid solution is used; however, these methodological differences do not lead to significant variations in their concentrations, and exert minimal influence on SB and CEC calculations in either classification system (Soil Survey Staff, 2011, 2014; Teixeira et al., 2017).

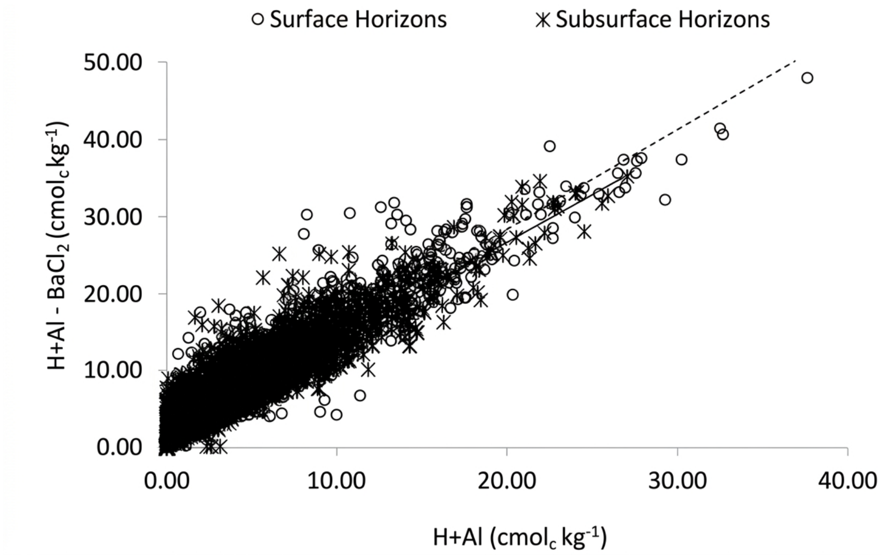

Figure 2. Scatterplot of H+Al values in SiBCS and $H+Al_{BaCl_2}$ in ST of the surface (n = 2,159) and subsurface (n = 3,628) horizons. Dashed trend line represents the surface horizons and the solid line represents the subsurface horizons.

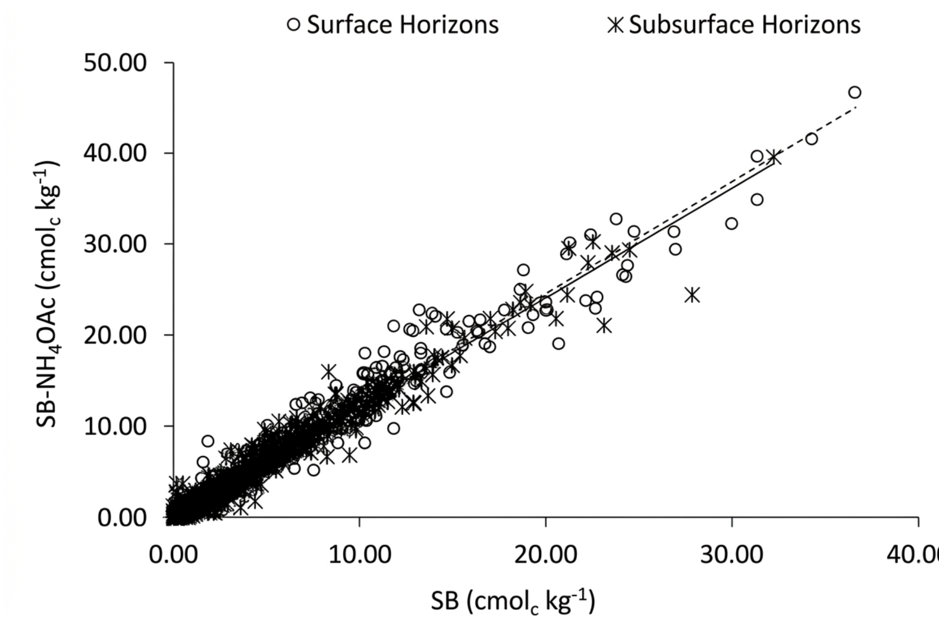

Figure 3. Scatterplot of SB values in SiBCS and SB_{NH4OAc} in WRB and ST of the surface (n = 1,693) and subsurface (n = 2,811) horizons. Dashed trend line represents the surface horizons, and the solid line represents the subsurface horizons.

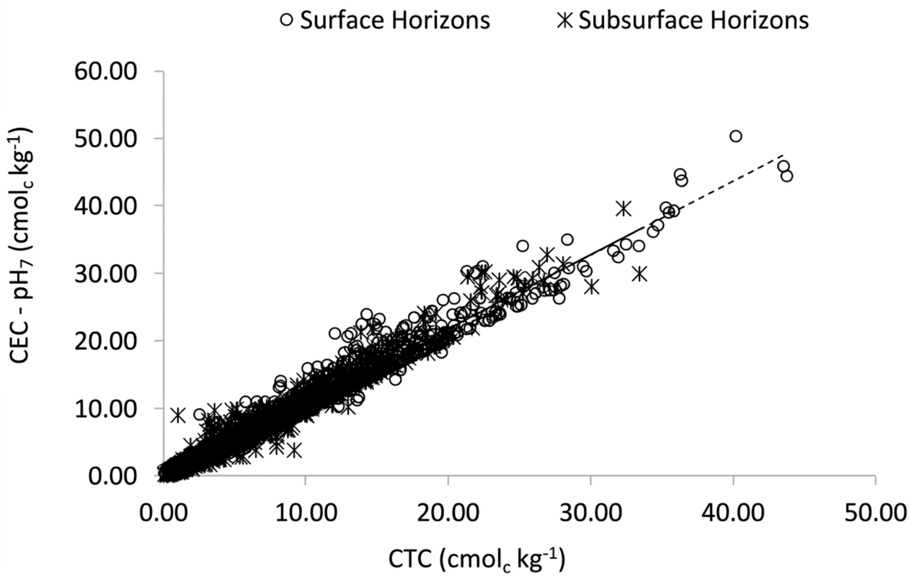

Figure 4. Scatterplot of CTC values in SiBCS and CEC_{pH7} in WRB and ST of the surface (n = 1,690) and subsurface (n = 2,795) horizons. Dashed trend line represents the surface horizons, and the solid line represents the subsurface horizons.

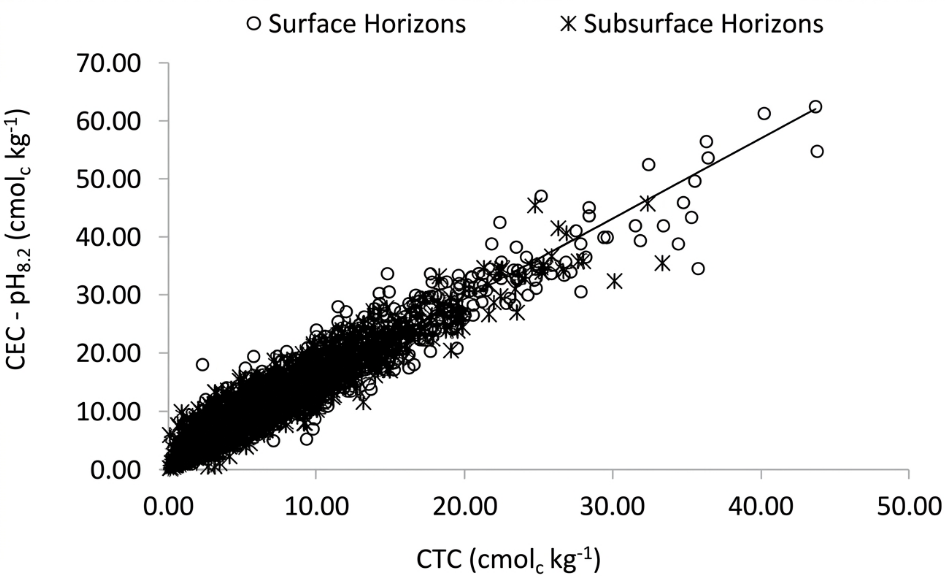

Figure 5. Scatter plot of CTC values in the SiBCS and $CEC_{pH8.2}$ in the ST of the surface (n = 1,690) and subsurface horizons (n = 2,795). Dashed trend line represents the surface horizons, and the solid line represents the subsurface horizons.

In the SiBCS, CTC is used to define the activity of the clay fraction (high-activity – ≥27.0 $cmol_c\ kg^{-1}$), while V is used to define the diagnostic surface *Chernozêmico* A horizon (≥65 %) and the eutrophic and dystrophic character (≥50 % and <50 %, respectively). These parameters are also used as diagnostic criteria in some subsurface soil classes, such as *Chernossolos* and *Luvissolos* (Santos et al., 2025). In the international systems, the CEC_{pH7} is used to define the activity of the clay fraction and to identify diagnostic horizons such as the ferralic (WRB) and oxic (ST).

In the WRB, V is also used to define eutric character (V = SB/CEC_e ≥50 %). In the Soil Taxonomy (ST), the eutrophic (V_{pH7} ≥ 50 or ≥ 60) and eutric (for the Oxisols order Acrustox and Acrudox ≥ 35 %) characters are defined using similar threshold values. In the WRB,

$CEC_{pH8.2}$ is applied only in special cases, such as to analyze saline or alkaline soils. The WRB also applies base saturation to define the Chernic and Mollic horizons and the soil groups Chernozems, Kastanozems, and Phaeozems; and the ST adopts this diagnostic property to define the Mollic epipedon and the Mollisols order.

The variations observed among analytical methods and proposals in this study are supported by a large number of soil samples representing a wide range of soil classes across Brazil. These results have important implications for soil classification in the SiBCS and for establishing correspondence of diagnostic property values among different soil classification systems.

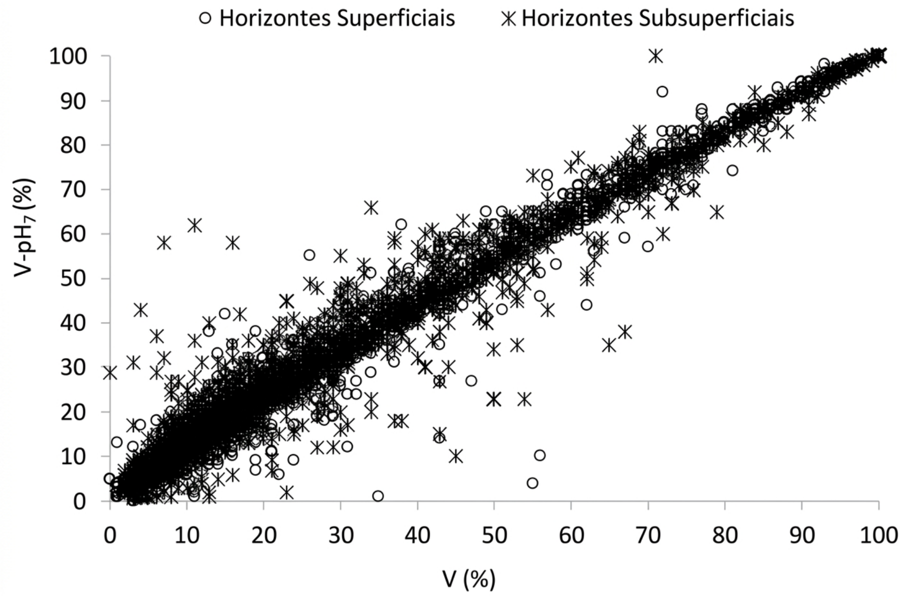

Figure 6. Scatter plot of V values in the SiBCS and V_{pH7} in the WRB and ST of the surface (n = 1,690) and subsurface horizons (n = 2,789). Dashed trend line represents the surface horizons, and the solid line represents the subsurface horizons.

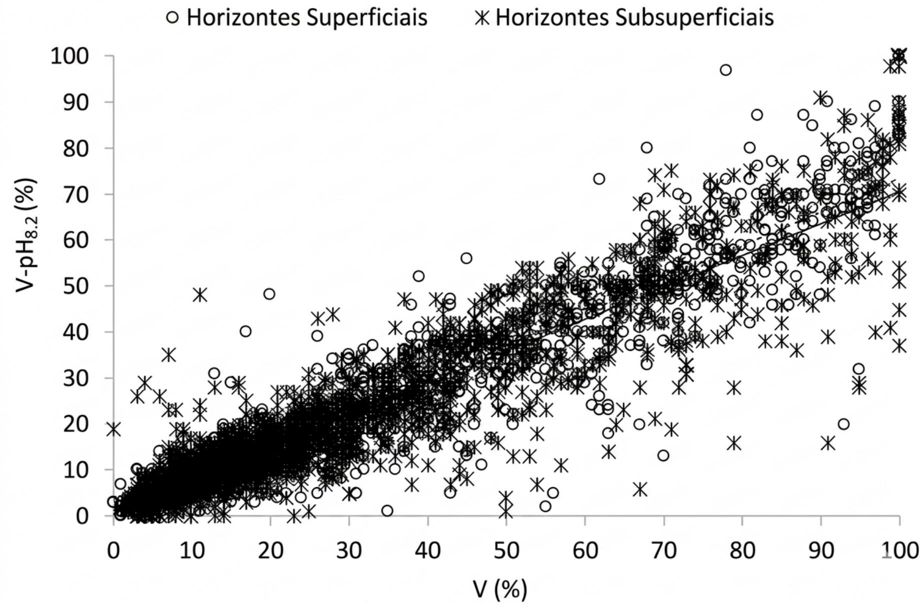

Figure 7. Scatterplot of V values in SiBCS and $V_{pH8.2}$ in ST of surface (n = 1,690) and subsurface (n = 2,789) horizons. Dashed trend line refers to surface horizons and solid line to subsurface horizons.

Table 4. Values of properties for subsurface horizons, calculated from exchangeable cations and potential acidity determinations obtained using the SiBCS, WRB, and ST methods

Statistic	SiBCS				WRB and ST					
	H+Al	SB	CTC_{pH7}	V	$H+Al_{BaCl_2}$	SB_{NH_4OAc}	CEC_{pH7}	$CEC_{pH8.2}$	V_{pH7}	$V_{pH8.2}$
	$cmol_c\ kg^{-1}$			%	$cmol_c\ kg^{-1}$				%	
Average	4.00 B	1.33 B	4.86 Bb	24 Ba	6.88 A	1.67 A	5.19 A	7.87a	27 A	18b
Median	3.20	0.44	3.88	15	6.00	0.60	4.08	6.49	18	11
Stand. Dev.	3.36	2.62	3.84	23	4.64	3.20	4.27	5.51	23	17
Minimum	0.00	0.00	0.13	0	0.00	0.02	0.13	0.23	1	0
Maximum	27.03	32.27	33.41	100	35.12	39.63	39.70	45.73	100	100
Count	**3,628**	**2,811**	**2,795**	**2,795**	**3,628**	**2,811**	**2,795**	**2,795**	**2,795**	**2,795**

Stand Dev: standard deviation; SB: sum of bases in SiBCS; SB_{NH_4OAc}: sum of bases in WRB and ST; CTC_{pH7}: cation exchange capacity in SiBCS; CEC_{pH7}: cation exchange capacity in WRB and ST; $CEC_{pH8.2}$: cation exchange capacity in ST; V: base saturation in SiBCS; V_{pH7}: base saturation in WRB and ST; $V_{pH8.2}$: base saturation in ST. Similar letters do not differ from each other when obtained by different methods according to the T-test at p<0.05.

Table 5. Predictive equations for estimating H+Al, SB, CEC and V values obtained by the analytical methods adopted in the SiBCS and the international WRB and ST systems for surface horizons

Property	Equation	R^2
H+Al ($cmol_c\ kg^{-1}$)	$= 0.6518 * H+Al_{BaCl_2} - 0.8057$	0.8407**
$H+Al_{BaCl_2}$ ($cmol_c\ kg^{-1}$)	$= 1.2898 * H+Al + 2.5588$	0.8407**
SB ($cmol_c\ kg^{-1}$)	$= 0.7914 * SB_{NH_4OAc} + 0.032$	0.9729**
SB_{NH_4OAc} ($cmol_c\ kg^{-1}$)	$= 1.2293 * SB + 0.0369$	0.9729**
CTC ($cmol_c\ kg^{-1}$)	$= 0.8868 * CEC_{pH7} + 0.3433$	0.9693**
CTC ($cmol_c\ kg^{-1}$)	$= 0.6614 * CEC_{pH8.2} - 0.4544$	0.9137**
CEC_{pH7} ($cmol_c\ kg^{-1}$)	$= 1.093 * CTC - 0.1335$	0.9693**
$CEC_{pH8.2}$ ($cmol_c\ kg^{-1}$)	$= 1.3815 * CTC + 1.642$	0.9137**
V (%)	$= 0.9598 * V_{pH7} - 1.4709$	0.9739#
V (%)	$= 1.2412 * V_{pH8.2} + 2.2201$	0.9098**
V_{pH7} (%)	$= 1.0147 * V + 2.2767$	0.9739#
$V_{pH8.2}$ (%)	$= 0.733 * V + 0.2039$	0.9098**

SB: sum of bases in SiBCS; SB_{NH_4OAc}: sum of bases in WRB and ST; CTC_{pH7}: cation exchange capacity in SiBCS; CEC_{pH7}: cation exchange capacity in WRB and ST; $CEC_{pH8.2}$: cation exchange capacity in ST; V: base saturation in SiBCS; V_{pH7}: base saturation in WRB and ST; $V_{pH8.2}$: base saturation in ST. Significance test: ** p<0.01; # p<0.10.

Table 6. Predictive equations for estimating H+Al, SB, CEC and V values obtained by the analytical methods adopted in the SiBCS and the international WRB and ST systems for subsurface horizons

Property	Equation	R^2
H+Al ($cmol_c\ kg^{-1}$)	$= 0.6466 * H+Al_{BaCl_2} - 0.449$	0.7974**
$H+Al_{BaCl_2}$ ($cmol_c\ kg^{-1}$)	$= 1.2332 * H+Al + 1.9478$	0.7974**
SB ($cmol_c\ kg^{-1}$)	$= 0.8083 * SB_{NH_4OAc} - 0.0188$	0.9697**
SB_{NH_4OAc} ($cmol_c\ kg^{-1}$)	$= 1.1997 * SB + 0.0731$	0.9697**
CTC ($cmol_c\ kg^{-1}$)	$= 0.8848 * CEC_{pH7} + 0.2638$	0.9695**
CTC ($cmol_c\ kg^{-1}$)	$= 0.6547 * CEC_{pH8.2} - 0.2985$	0.8856**
CEC_{pH7} ($cmol_c\ kg^{-1}$)	$= 1.0957 * CTC - 0.1308$	0.9695**
$CEC_{pH8.2}$ ($cmol_c\ kg^{-1}$)	$= 1.3526 * CTC + 1.3045$	0.8856**
V (%)	$= 0.958 * V_{pH7} - 2.2877$	0.9541#
V (%)	$= 1.2413 * V_{pH8.2} + 1.7502$	0.8595**
V_{pH7} (%)	$= 0.9959 * V + 3.5169$	0.9541#
$V_{pH8.2}$ (%)	$= 0.6924 * V + 1.2599$	0.8595**

SB: sum of bases in SiBCS; SB_{NH_4OAc}: sum of bases in WRB and ST; CTC_{pH7}: cation exchange capacity in SiBCS; CEC_{pH7}: cation exchange capacity in WRB and ST; $CEC_{pH8.2}$: cation exchange capacity in ST; V: base saturation in SiBCS; V_{pH7}: base saturation in WRB and ST; $V_{pH8.2}$: base saturation in ST. Significance test: ** p<0.01; # p<0.10.

Regarding the correspondence of soil classes between the SiBCS and international systems, the V (SiBCS) value estimated through equations derived from V_{pH7} (WRB and ST) may differ by up to approximately 5 % for both surface and subsurface horizons. This variation can be considered negligible given the own analytical uncertainty of the methods. Therefore, a direct correspondence between the values obtained by both methods to be adopted in the SiBCS is proposed in this study. Consequently, no distinction exists between the V of the Mollic epipedon (ST), the Chernic and Mollic horizons (WRB), and the eutrophic or dystrophic characters as defined by SiBCS, WRB, and ST.

In addition, for the SiBCS, the small difference observed justifies a revision of the threshold values defining diagnostic horizons, particularly the V criterion, currently set at ≥65 %. Revising this limit could significantly affect the geographic distribution of the order *Chernossolos* in the Brazilian territory, as well as of classes of soils with chernozemic A horizons.

The proposed adjustment of V% will also affect the classification of anthropic soils and those modified by management practices, such as liming, thereby enabling better interpretation of their potential and limitations for agriculture.

CONCLUSIONS

The values of potential acidity (H+Al), sum of bases (SB), cation exchange capacity (CEC), and base saturation (V) obtained using the analytical methods adopted by the SiBCS are lower than those obtained using the methods of the international systems WRB and ST. For the V values, the difference between methods is approximately 5 %; therefore, a direct correspondence between the different methods can be considered acceptable, except for $V_{pH8.2}$, for which the use of predictive equations is recommended.

For the diagnostic surface *Chernozêmico* A horizon, the current 65 % V threshold underestimates the occurrence of this horizon and the soil classes in which it is found across Brazil. Adjusting the threshold to define the eutrophic character in surface horizons, in accordance with international classification criteria, will provide a more accurate representation of the soil fertility and the geographic distribution of these soils.

DATA AVAILABILITY

The data will be provided upon request.

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Visualization: Ademir Fontana (lead) and Lúcia Helena Cunha dos Anjos (supporting).

Writing – original draft: Ademir Fontana (lead), Alessandro Samuel-Rosa (supporting), Lúcia Helena Cunha dos Anjos (supporting) and Taciara Zborowski Horst (supporting).

Writing – review & editing: Ademir Fontana (equal), Alessandro Samuel-Rosa (supporting), Lúcia Helena Cunha dos Anjos (supporting) and Taciara Zborowski Horst (supporting).

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