Spectral patterns in the mid-ir of soils in the northeast of Brazil and their relation to the taxonomic classification

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A B S T R A C T

Knowing particularities of soils allows the adoption of sustainable management practices. The most efficient method to obtain data on the soil is through its characterization, essential for planning land use and soil conservation. However, soil surveys conducted in the conventional methods are costly and time-consuming. This study aimed to identify spectral patterns in the mid-IR wavelengths for a quick and low cost characterization of soil classes. Soils from the Natuba river basin, Pernambuco State, Brazil, were used. These soils were mapped on a scale of 1:25,000, where the presence of *Latossolos, Argissolos, Gleissolos and Neossolos* were identified. The data of reflectance for profiles of each soil class were collected using the spectral range between 2,500 and 25,000 nm. In the mid-IR region, *Latossolos* and *Argissolos* presented spectral characteristics peculiar to classification criteria. The increased contents of organic matter and iron oxides reduced soil reflectance. The horizons with sand content above 80% showed strong absorption spectra and significant reflectance peaks of quartz in the mid-IR. The wavelengths 2,681, 2,600 and 2,495 cm^{-1} occurred only in these horizons. The spectral analysis presented as a high-potential method for the characterization and classification of soils.
Keywords: spectral patterns, reflectance, soil absorption features, organic matter, iron oxide.

Padrões espectrais no infravermelho médio de solos do nordeste do Brasil e sua relação com a classificação taxonômica

R E S U M O

Conhecer as particularidades dos solos possibilita a adoção de práticas de manejo sustentáveis. O método mais eficiente de obter dados a respeito do solo é por meio de caracterizações pedológicas, indispensáveis ao planejamento de uso e conservação das terras. Porém, o levantamento de solos pelo método convencional, principalmente os mais detalhados, são onerosos e demorados. Diante do exposto, o objetivo deste trabalho foi identificar padrões espectrais na faixa do infravermelho médio em laboratório que permitam a caracterização de classes de solos de forma rápida e a baixos custos. Foram utilizados os solos da região da sub-bacia do rio Natuba, Pernambuco, Brasil. Estes solos já possui uma classificação convencional na escala de 1:25.000, em que a presença de Latossolos, Argissolos, Gleissolos e Neossolos foram identificados. Na região do MIR, os Latossolos e Argissolos apresentaram caraterísticas espectrais peculiares aos critérios de classificação. O aumento dos teores de matéria orgânica e óxidos de ferro reduziram a reflectância dos solos. Os horizontes com teor de areia acima de 80% exibiram fortes bandas de absorção e fortes picos de reflectância de quartzo na faixa do MIR. As feições espectrais de 2681, 2600 e 2495 cm^{-1} ocorreram apenas nesses horizontes. A análise espectral se apresentou como um método de alta potencialidade para a caracterização de solos.
Palavras-chave: padrões espectrais, reflectância, feições de absorção do solo, matéria orgânica, óxido de ferro

Introduction

The soil is one of the natural resources in greater abundance on the earth's surface and of utmost importance for food production (Gallardo, 1998). As it is considered a basic, vital and nonrenewable resource, soil productivity depends on its fertility (Hartemik and McBratney, 2008), which is reduced when the soil is used beyond its maximum capacity. This is because the soils present specific conditions of use and handling, which are directly related to their physical, chemical and mineralogical features (Guerra et al., 2007; Bertoni and Lombardi Neto, 2008). Thus, knowing the particularities of soils allows the adoption of sustainable management practices (Nanni et al., 2004; Bertoni and Lombardi Neto, 2008).

The most efficient method to obtain information about the soil is through soil mapping (Nanni et al., 2004), which is an essential tool for planning land use and soil conservation (Bellinaso et al., 2010). However, the mapping of soils, especially detailed mapping, is relatively costly and time-consuming because of the high costs of laboratory testing, hard fieldwork and lack of specialized professionals to run lab tests (Demattê, 2002; McBratney et al., 2003; Viscarra Rossel and McBratney, 2008). These difficulties, along with the great territorial extension and regional differences in Brazil, lead to the implementation of soil surveys on small scales that do not provide enough information for the proper management of soils (Santos and Santos, 2007). Pernambuco is one of the few Brazilian states that has all its territory mapped at the scale 1:100,000 (Silva et al., 2001); nevertheless, there is need to use larger scales, which makes the task more challenging due to the high costs involved.

Given the problems to carry out detailed soil surveys, there is a growing interest in the use of remote sensing techniques, as it allows obtaining information quickly, cheaply and efficiently without causing pollution, when compared to conventional laboratory and field techniques (Demattê and Garcia, 1999; Viscarra Rossel et al., 2006). The initial investment to purchase a laboratory sensor, such as a spectroradiometer, may seem expensive at first, around US$ 100,000; however, the financial return is guaranteed by the reduction of costs with laboratory testing (Viscarra Rossel and McBratney, 2008). Sousa Junior et al. (2015) identified a cost of US$ 151,888.15 to analyze soil samples by the conventional method; however, costs reduced to US$ 76,192.10 using the spectral method. Spectral analyses, besides cheaper, are not destructive and do not use chemical reagents. Therefore, they do not generate waste and require minimum preparation to analyze the sample with just a few grams that is only dried and homogenized to a particle size smaller than 2 mm, which makes the analyses faster. According to Cohen et al. (2007), errors in the spectral analysis at most similar or lower than those made by conventional laboratory tests. Janik et al. (1998) state that spectroradiometry has an advantage over many other techniques of soil analysis, as it has sensitivity to identify the soil organic and inorganic phases. The spectral method allows the use of a greater number of samples without raising the costs, enabling a large-scale survey (Nanni and Demattê, 2006).

Reflectance spectroradiometry in laboratory (ground level), increasingly used in soil studies, aims to measure the electromagnetic radiation reflected by soil samples in different wavelengths. The graphic representation of these measurements, called the spectral reflectance curve, allows identification and characterization of soil physical and chemical attributes from their relationships with the spectra (Demattê and Garcia, 1999; Madeira Netto, 2001), since the interaction between soil constituents and radiation occurs in specific wavelengths (Andronikov and Dobrovolskiy, 1991).

The main regions of the electromagnetic spectrum used in soil studies correspond to the visible (VIS: *visible*) from 350 to 700 nm, the near infrared (NIR: *near infrared*) from 700 to 2500 nm, subdivided into shortwave infrared (SWIR/ *shortwave infrared*) from 1100 to 2500 nm (Stoner and Baumgardner, 1981; Formaggio et al., 1996; Clark, 1999; Demattê, 2002; Dalmolin et al., 2005; Ben-Dor et al., 2008), as well as the mid-infrared (MIR: *mid infrared*) from 2500 to 25000 nm, which is subdivided into thermal infrared (TIR/*thermal infrared*) from 8000 and 14000 nm (Madari et al., 2005; Viscarra Rossel et al., 2006; Reeves III, 2010).

Spectral characterizations carried out in the VIS/NIR (350 to 2500 nm) and mid-IR (2500 to 25000 nm or 4000 to 400 cm^{-1}) exhibit distinct spectral peculiarities and contain important information about soil organic and inorganic compounds (Viscarra Rossel and McBratney, 2008). The VIS/NIR region has a few and plain absorption features, while the mid-IR presents a number of absorption features related to the functional groups of organic and mineral compounds in the soil (Viscarra Rossel and McBratney, 2008).

The spectral curves of mid-IR are characterized qualitatively by means of positive and negative absorption peaks that correspond

mainly to clay minerals, quartz and organic compounds (Janik et al., 1998; Viscarra Rossel et al., 2006; Nayak and Singh, 2007). The spectral bands in the mid-IR region are formed from fundamental molecular vibrations, unlike the VIS/NIR, which has its bands produced by non-fundamental vibrations, "overtones" and "combinations", that is, secondary vibrations, which are much less intense than fundamental vibrations. Fundamental vibrations allow the mid-IR to display spectral curves with absorption waves in greater numbers and more pronounced (Madeira Netto, 2001; Viscarra Rossel et al., 2006; Viscarra Rossel and McBratney, 2008), containing much more information about the mineralogy and organic composition of soils than the VIS/NIR region (Janik and Skjemstad, 1995).

The large number of papers published internationally (Ben-Dor et al., 2008; Stenberg et al., 2010) and nationally (Formaggio et al., 1996; Demattê and Garcia, 1999; Madeira Netto, 2001, Demattê, 2002; Demattê et al., 2004; Nanni and Demattê, 2006; Demattê and Terra, 2014) prove the effectiveness of studies related to the interaction of electromagnetic radiation with the soil in the VIS/NIR region. However, in the case of the mid-IR, few studies have been conducted internationally (Janik et al., 1998; Viscarra Rossel et al., 2008; Minasny et al., 2009) and nationally (Madari et al., 2005;mTerra et al., 2015), even though it is a region that presents far more spectral information of the soil than does the VIS/NIR.

In the case of soils, it must be understood that this technique does not exempt the fieldwork. Still, the possibility to identify and characterize soils makes spectroradiometry an important tool (Viscarra Rossel et al., 2006; Lagacherie et al., 2008), which is still little used in northeastern Brazil.

The study site is the Natuba River basin, which has a pedological map on a scale of 1:25,000 (Araújo Filho et al., 2013). The watershed is an important region for family agriculture in the state of Pernambuco, which has as its main economic activity the production of the leafy vegetable on a large scale, characterized by continuous, unsuitable and useless procedures of management practices and soil conservation. Thus, the question is how to obtain accurate information on soils of agricultural regions such as the Natuba River basin if the mappings in detailed scale are costly and time consuming.

Therefore, this study, with lab spectroradiometry in the mid-IR, aimed to characterize the soils in the region of the Natuba River basin in order to help soil classifications and generate information to plan land use and management and soil conservation. It is expected that this spectral range detect soil attributes that allow soil classification.

Material and methods

The study site was the Natuba River basin, located in the Zona da Mata of Pernambuco State, Brazil (Fig. 1), for which there is already a semi-detailed pedological survey (Araújo Filho et al., 2013) up to the 4th categorical level (Table 1) according to the Brazilian System of Soil Classification – SiBCS (EMBRAPA, 2018) on a scale 1:25,000.

Samples from horizons of 15 soil profiles representative of basin were collected, totaling 70 samples. The physical and chemical characterization of soils is available in Araújo Filho et al. (2013).
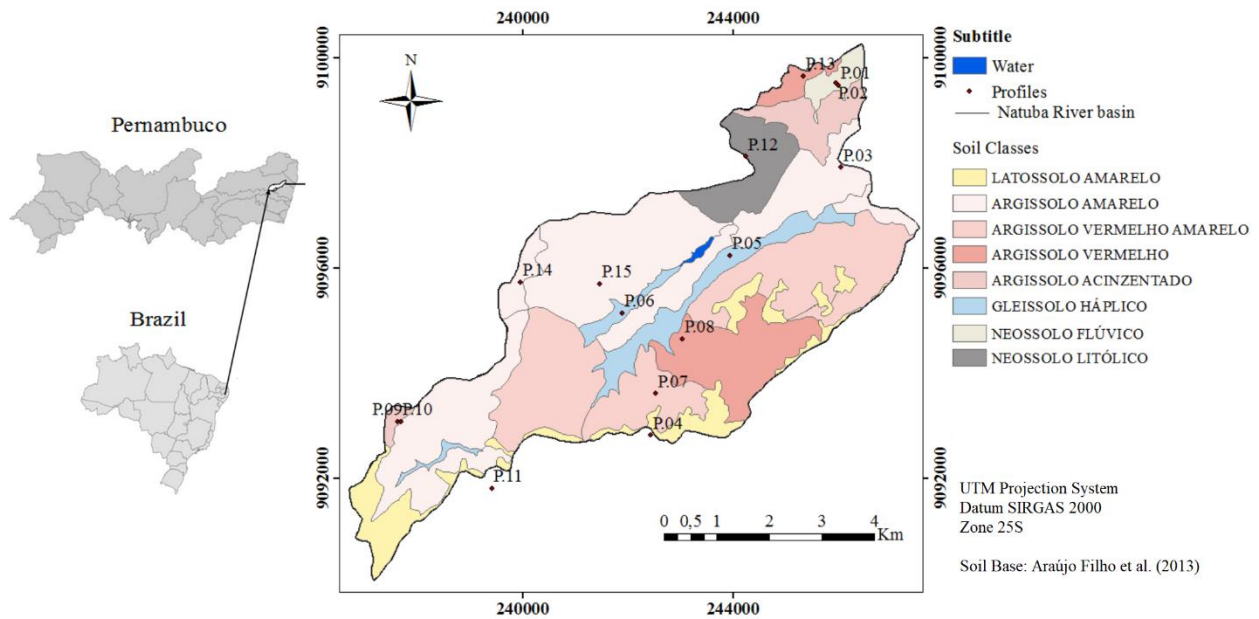
Figure 1. Natuba River basin and its distribution of soil classes, located in the Zona da Mata of Pernambuco State, Brazil.

Table 1. Soil classification up to the fourth hierarchical level of the Brazilian System of Soil Classification, located in the Natuba River basin, Zona da Mata of Pernambuco State, Brazil.

Profile	Soil classes
P1	*ARGISSOLO ACINZENTADO Distrocoeso epirredóxico*
P2	*NEOSSOLO FLÚVICO Ta Eutrófico solódico gleissólico*
P3	*ARGISSOLO VERMELHO-AMARELO Distrófico léptico*
P4	*LATOSSOLO AMARELO Distrocoeso típico*
P5	*GLEISSOLO HÁPLICO Sódico típico*
P6	*GLEISSOLO HÁPLICO Ta Eutrófico solódico*
P7	*ARGISSOLO AMARELO Distrocoeso endorredóxico*
P8	*ARGISSOLO VERMELHO Distrófico típico*
P9	*ARGISSOLO ACINZENTADO Distrocoeso epirredóxico*
P10	*ARGISSOLO AMARELO Distrocoeso endorredóxico*
P11	*LATOSSOLO AMARELO Distrocoeso úmbrico*
P12	*NEOSSOLO LITÓLICO Distrófico fragmentário*
P13	*ARGISSOLO VERMELHO Eutrófico abrúptico solódico*
P14	*ARGISSOLO AMARELO Distrocoeso úmbrico plíntico*
P15	*ARGISSOLO VERMELHO-AMARELO Distrocoeso epirredóxico*

Mineralogical analysis

For the analysis of mineralogy, diagnostic horizons of each soil profile and more the surface horizon of the *LATOSSOLO AMARELO Distrocoeso típico* (P4) were selected. The identification of the minerals in the clay fraction was performed by x-ray diffraction (DRX) (DIXON et al., 2002).

Diffuse reflectance: 2500 to 25000 nm or 4000 to 400 cm^{-1} (MIR)

The spectral data were obtained with the Nicolet 6700 FT-IR sensor with an accessory to capture diffuse reflectance (Smart Diffuse Reflectance). The HeNe laser was used a light source and was positioned internally and with a calibration standard for each wavelength (2500 to 25000 nm). The spectra were acquired with 1.2 nm spectral resolution with 64 readings per spectrum every second. For the analyses, approximately 1 cm^3 of the sample was used, which as ground at 100-mm mesh, and placed in the sensor compartment. For each measurement, the system was calibrated to obtain the reference spectrum with a gold plate (background spectrum). The spectral curves were generated in wave numbers (cm^{-1}) between 4000 and 400 cm^{-1}, which is equivalent to the wavelength range from 2500 to 25000 nm.

After obtaining the spectral readings, the data were stored, organized and processed. The spectral measurements were corrected to eliminate equipment noise. The measurements were saved in the txt format and inserted into the spreadsheet to calculate the spectral averages of each sample and construct the graphs (reflectance by wavelength and wave number).

Soil characterization based on the spectral curves

The characterization of soils based on the spectral curves was based on the descriptive method used by Demattê et al. (2015). This method is based on the morphological analysis of soil spectrum and contains three fundamental points: reflectance intensity, absorption features and the general shape of the individual curves (Demattê, 2002). The morphological characteristics of the spectral curves were related to the chemical, physical and mineralogical attributes of the soil. The qualitative assessments of 15 profiles were made by soil class to check for the existence of spectral features peculiar to each class. Each profile was characterized separately and then compared with the other sections of its order. The spectral morphology of each soil class was compared to one another. To identify the spectral patterns, the properties of the soil classes were associated with the spectral characteristics, according to taxonomic criteria (Stoner and Baumgardner, 1981).

Results and discussion

The spectral behavior of the classes of *Latossolos* in the mid-IR region (Figs. 2 and 3) showed peculiar standards belongin to the first categorical level of SiBCS (EMBRAPA, 2018). The mitigation of the absorption features of clay minerals and quartz in the spectral curve and the presence of a wave that was more open and shallow in 1624 cm^{-1} were considered peculiar spectral patterns consistent with the presence of *Latossolos* as they are related to pedological development of a high degree of weathering (Fig. 4).

Another spectral pattern was observed with respect to the subtle difference between the reflectance intensity in the spectral curves of *Latossolos* due to low textural variation at depth, typical of this soil class (Table 2). Terra *et al.* (2015) also identified reduction of the waves for the phyllosilicates and for the quartz features in classes of *Latossolos*, in addition to the fairly similar albedo between the curves. The *Latossolos* showed a similar pattern for the VIS/NIR region. Spectral patterns common to the 2nd (color), 3rd (Distrocoeso) and 4th (umbric and typical) categorical levels were not identified.

For the class of *Argissolos*, peculiar spectral patterns were identified at the 1st categorical level (Fig. 5). The greater reflectance intensity of the spectral curve of the *Ap* horizon, with peaks of reflectance from 1350 cm^{-1}, are characteristic patterns of *Argissolos* featuring sandy texture in the upper horizon, due to the process of clay translocation to the lower horizons. The absorption feature, which is more elongated and deeper in 1624 cm^{-1} region in Bt2 and C/Cr horizons, is attributed to the higher clay content and smaller presence of organic matter in subsurface horizons of *Argissolos* (Table 3). Spectral patterns were not observed for the other categorical levels.
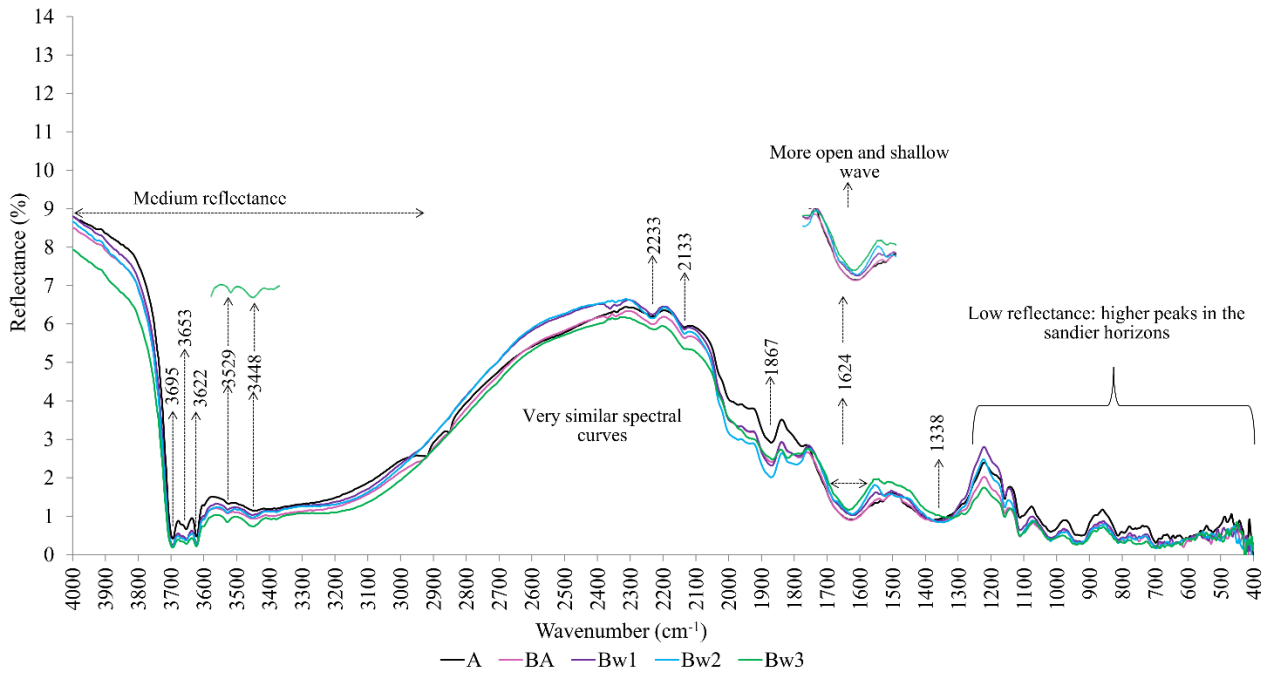
Figure 2. Spectral curve in the mid-IR region of the *LATOSSOLO AMARELO Distrocoeso típico* (P4), located in the Natuba River basin, Zona da Mata in Pernambuco State, Brazil.
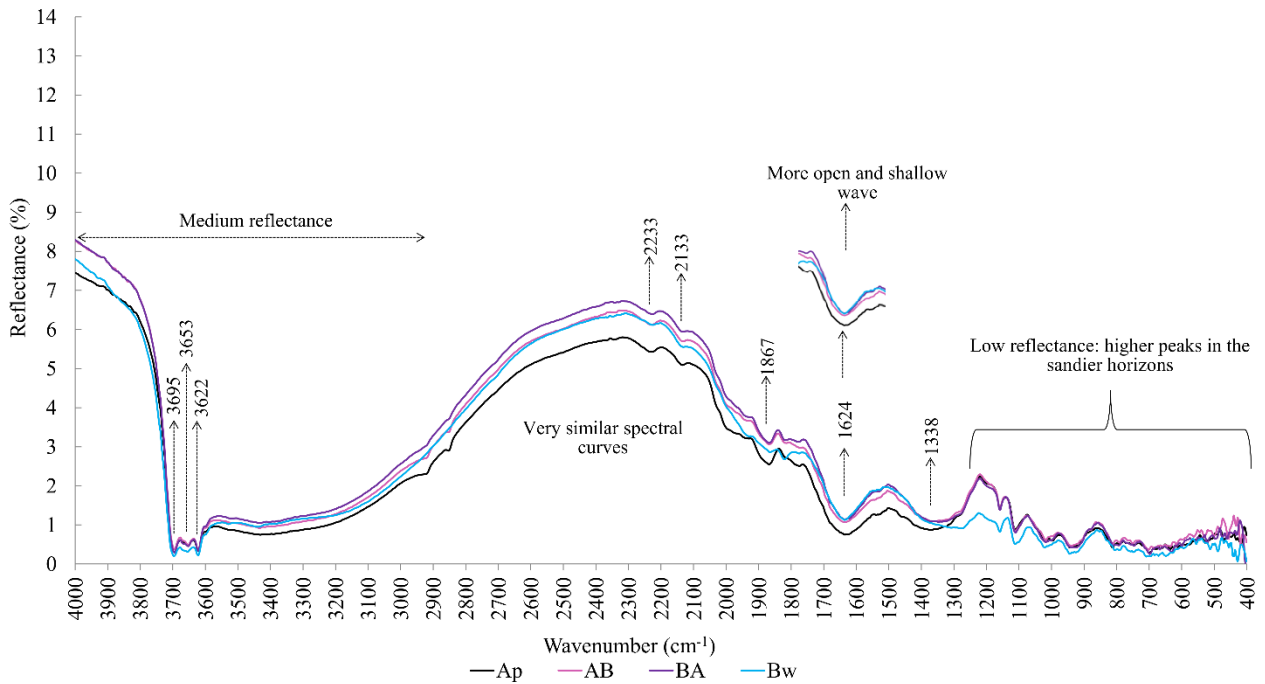

Figure 3. Spectral curve in the mid-IR region of the *LATOSSOLO AMARELO Distrocoeso úmbrico* (P11), located in the Natuba River basin, Zona da Mata in Pernambuco State, Brazil.
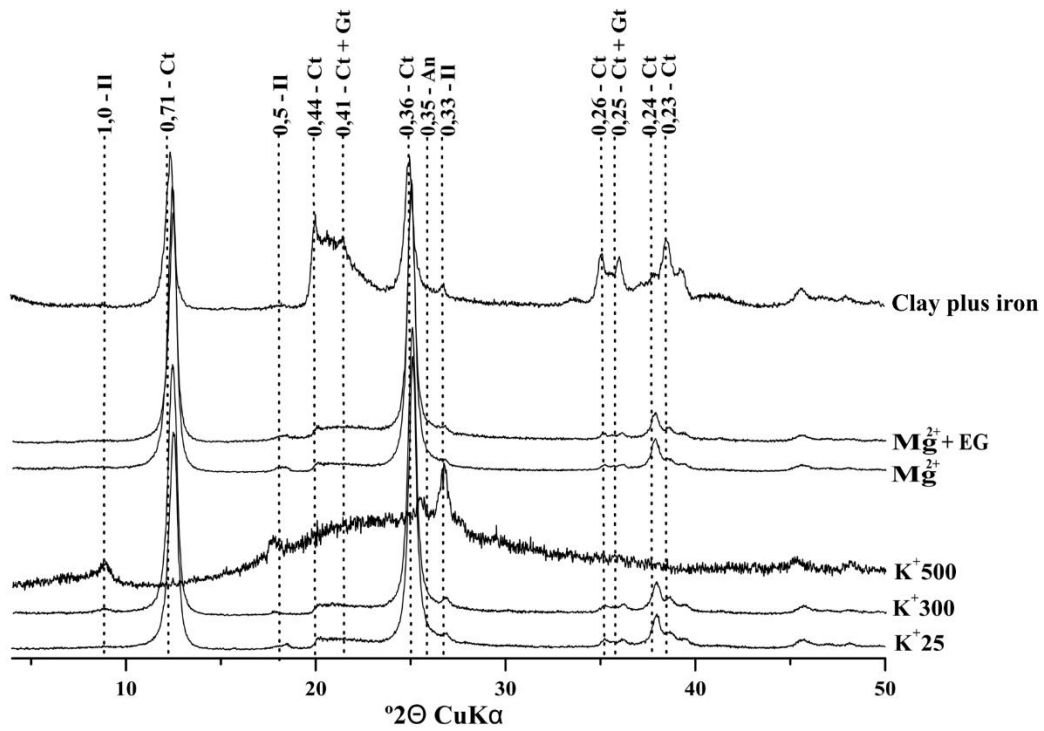
Figure 4. X-ray diffractogram of the clay fraction of the Bw horizon (52-160 cm) of the LATOSSOLO AMARELO Distrocoeso úmbrico (P11), located in the Natuba River basin, Zona da Mata in Pernambuco State, Brazil. Ct = Kaolinite; Il = Illite; Qz = Quartz; Gt = Goethite; Na = Anatase.

Table 2. Values of particle size and organic matter of the horizons of the *LATOSSOLO AMARELO Distrocoeso típico* (P4), located in the NatubaRiver basin, Zona da Mata in Pernambuco State, Brazil.

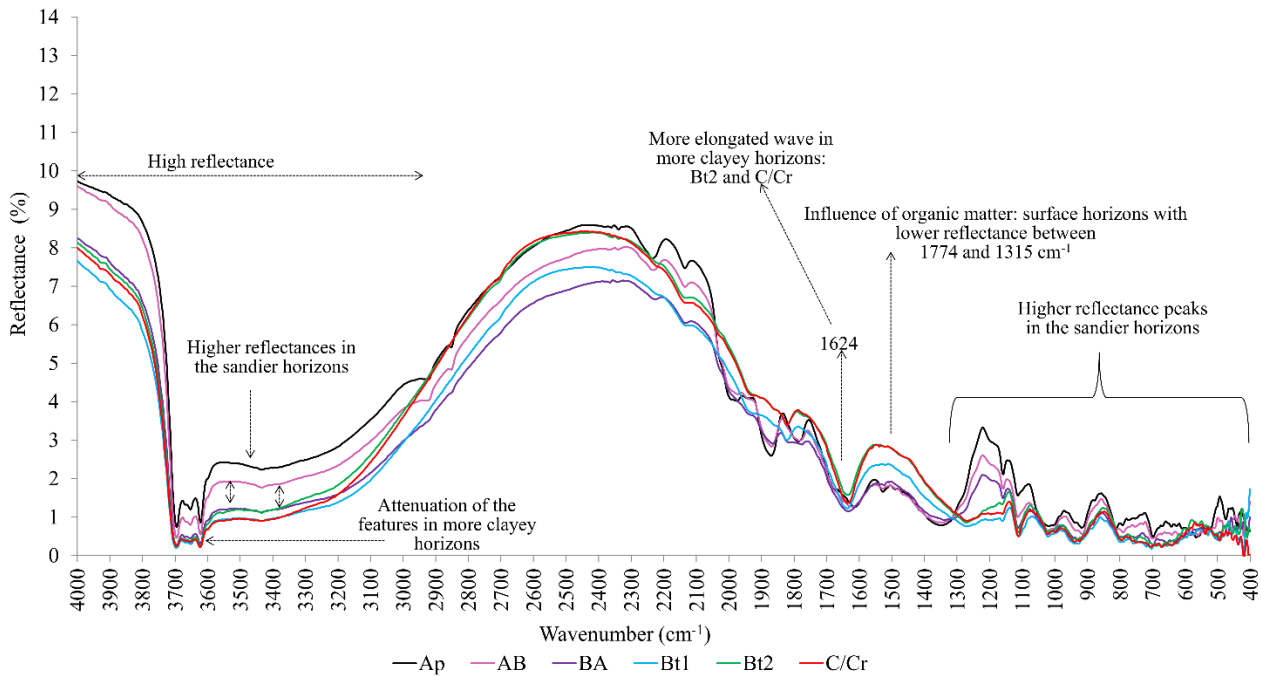| Attributes	Horizon/Depth				
	A	BA	Bw1	Bw2	Bw3
	0-13	13-28	28-60	60-130	130-190
	------------------------g kg^{-1}------------------------				
Coarse sand (2 – 0.2)	327	302	271	302	227
Fine sand (0.2 – 0.05)	148	133	136	146	127
Silt (0.05 – 0.002)	275	295	303	242	296
Clay (< 0.002)	250	270	290	310	350
Organic matter	33.6	18.3	8.1	4.7	4.5

Figure 5. Spectral curve in mid-IR region of the *ARGISSOLO VERMELHO Distrófico típico* (P8), located in the Natuba River basin, Zona da Mata in Pernambuco State, Brazil.

Table 3. Values of particle size and organic matter of the horizons of the *ARGISSOLO VERMELHO Distrófico típico* (P8), located in the Natuba River basin, Zona da Mata in Pernambuco State, Brazil.

Attributes	Horizon/Depth				
	Ap	AB	BA	Bt1	Bt2
	0-16	16-33	33-55	55-100	100-160
	--------------------------g kg^{-1}--------------------------				
Coarse sand (2 – 0.2)	432	360	277	168	204
Fine sand (0.2 – 0.05)	215	193	125	82	135
Silt (0.05 – 0.002)	183	237	268	340	331
Clay (< 0.002)	170	210	330	410	330
Organic matter	19.31	14.48	3.45	3.10	3.28

The spectral features common to *Gleissolos* were the absence of wave 3653 cm^{-1} and the enhancement of the feature in 3622cm^{-1}, related to smectite (Figs. 6 and 7). Although *Gleissolos* present a sodium character, sodium did not significantly correlated with reflectance and absorption. Moreover, it was not observed spectral characteristics that could be related to categorical levels in SiBCS (EMBRAPA, 2018).
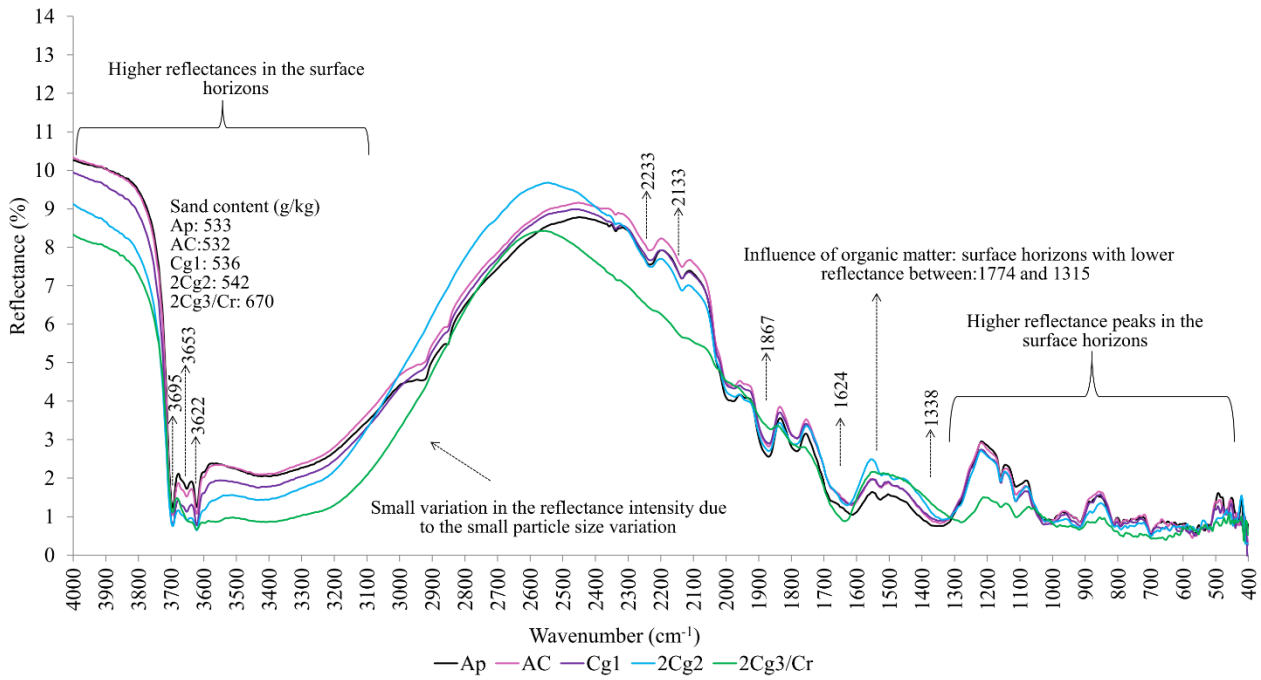
Figure 6. Spectral curve in the mid-IR region of the *GLEISSOLO HÁPLICO Sódico típico* (P5), located in the Natuba River basin, Zona da Mata in Pernambuco State, Brazil.
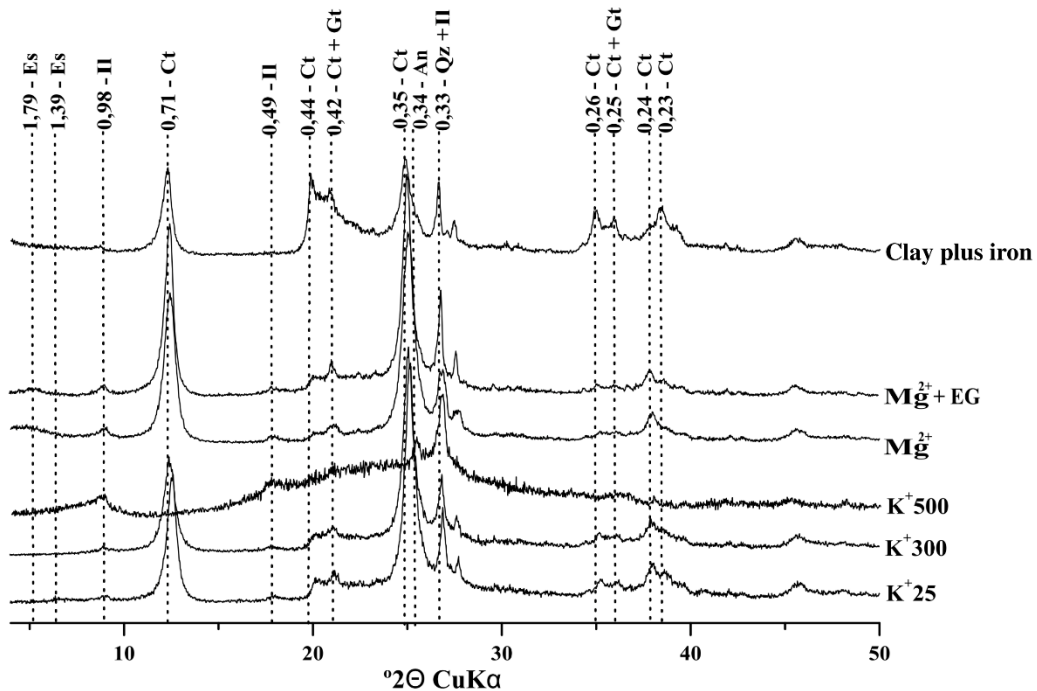

Figure 7. X-ray diffractograms of the clay fraction in horizon Cg2 (25-60 cm) of the *GLEISSOLO HÁPLICO Ta Eutrófico solódico* (P6), located in the Natuba River basin, Zona da Mata in Pernambuco State, Brazil. Es = Smectite; Ct = Kaolinite; Il = Illite; Qz = Quartz; Gt = Goethite; An = Anatase.

NEOSSOLOS exhibited reflectance with intensity between 10 and 13% (Figures 8 and 9). The *NEOSSOLO FLÚVICO Ta Eutrófico solódico gleissólico* (profile 2) presented high reflectance in the whole electromagnetic spectrum, with strong absorption waves in 3695, 3653 and 3622 cm^{-1} associated to illite and, in smaller proportion, to kaolinite (Fig. 10), mainly in the sandier horizons (Table 4). Quartz features were highly pronounced in 2233, 2133, 1867, 1786, 1624, 1338 and 694 cm^{-1} and occurred in the sandier horizon 3C4. Smooth waves in 2681, 2600, 2495 cm^{-1} were also observed in 3C4 and 4Cg horizons probably associated with quartz. The same traits were found in 2Cg3 horizon

of *GLEISSOLO HÁPLICO Ta Eutrófico solódico* (profile 6), which also featured a fairly high sand content (897g/kg^{-1}) (Fig. 6). The wave 1624 cm^{-1} was narrower for the sandier 3C4 and 4Cg horizons due to the presence of quartz and clay minerals 2:1.
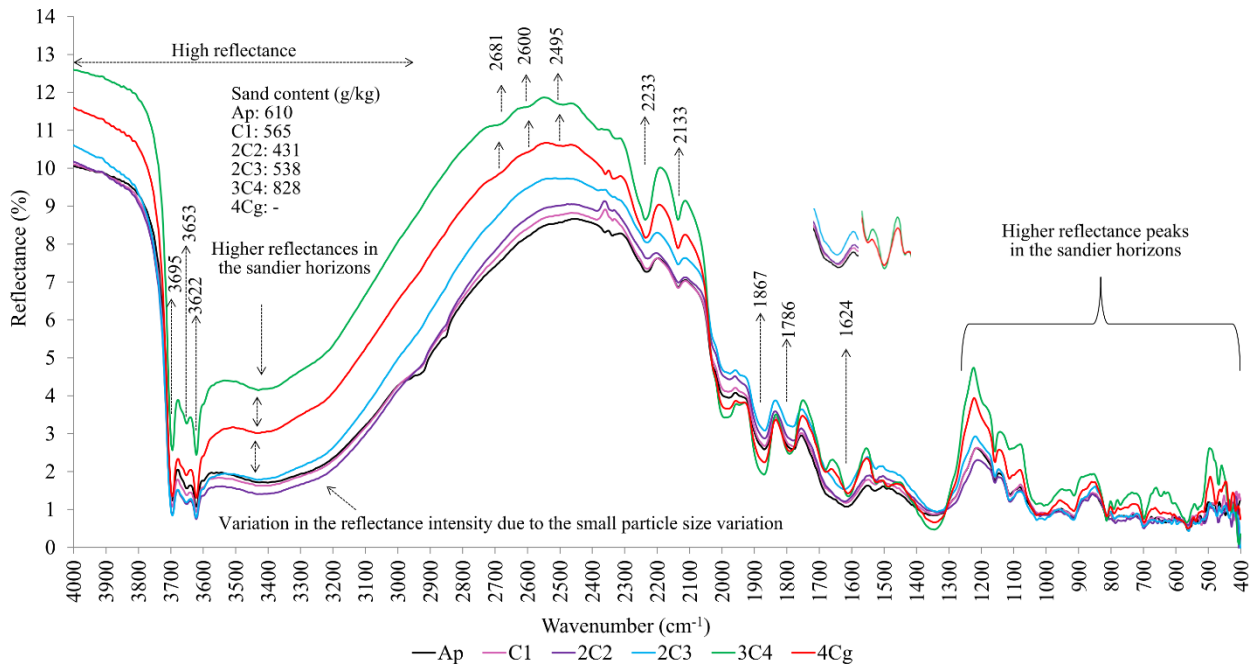

Figure 8. Spectral curve in the mid-IR region of the NEOSSOLO FLÚVICO Ta Eutrófico solódico gleissólico (P2), located in the Natuba River basin, Zona da Mata in Pernambuco State, Brazil.

NEOSSOLO LITÓLICO Distrófico fragmentário presented absorption features corresponding to quartz, smoother in 2233, 2133 and 1975 cm^{-1} and more pronounced in 1867, 1786, 1624 and 1338 cm^{-1} (Fig. 9). The *Ap* horizon exhibited more pronounced waves for being a little grittier. Waves 3695 and 3622 cm^{-1} displayed a more elongated shape, and the wave 3695 cm^{-1} referred to illite and kaolinite and the feature 3622 cm^{-1} to smectite (Fig. 11). The horizons were very similar in the spectral behavior and had little difference in reflectance intensity and absorption features as they presented very similar contents of sand and clay. The peak reflectance influenced by quartz above 1300 cm^{-1} showed average reflectance intensity. Peculiar spectral patterns were not observed for the classes of *Neossolos* that associate to their respective categorical levels in Brazilian Soil Classification System (EMBRAPA, 2018).
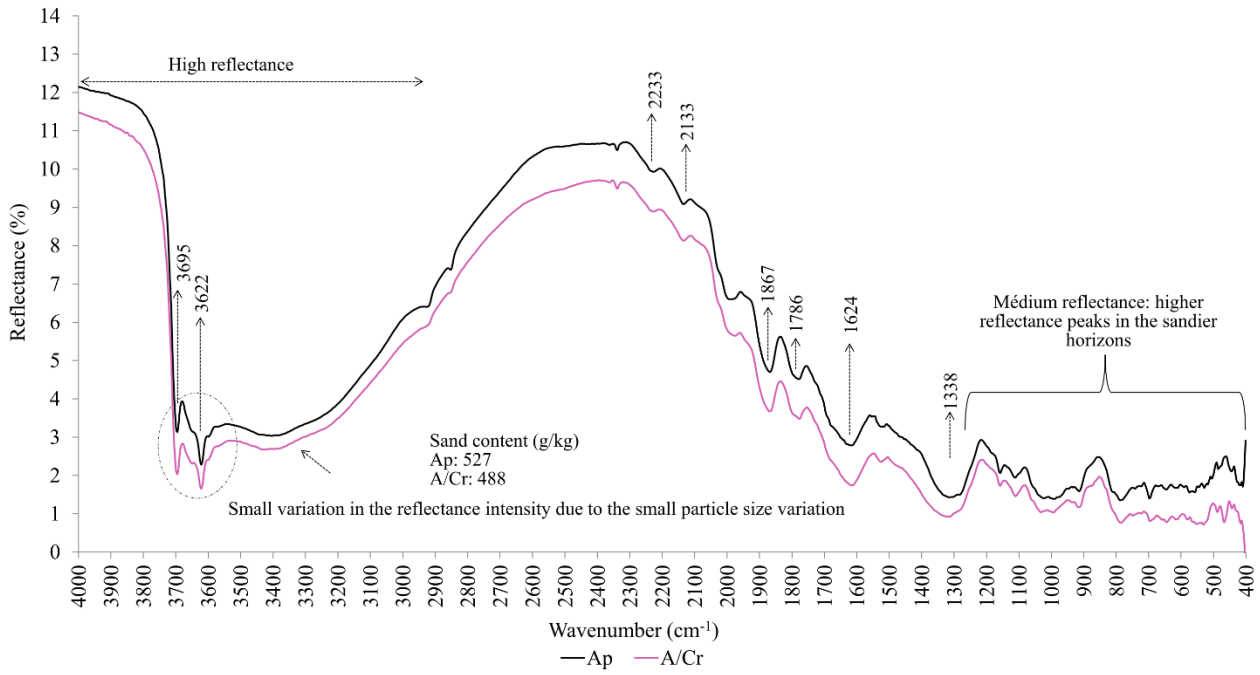
Figure 9. Spectral curve in the mid-IR region of the NEOSSOLO LITÓLICO Distrófico fragmentário (P12), located in the Natuba River basin, Zona da Mata in Pernambuco State, Brazil.
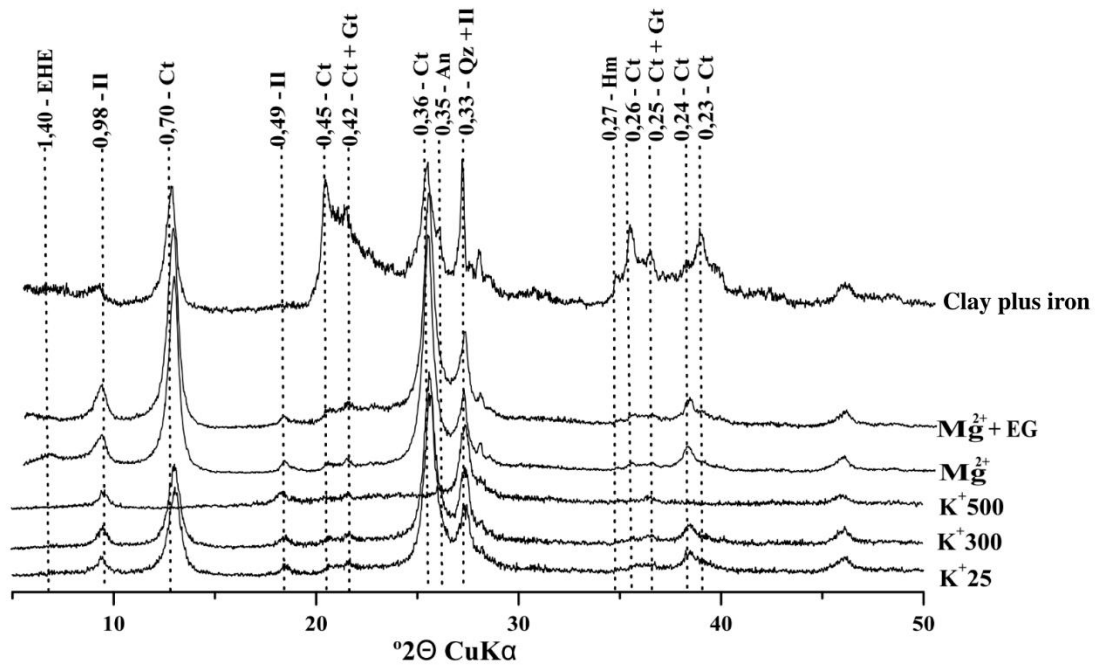

Figure 10. X-ray diffractograms of the clay fraction in the 2C2 horizon (30-80 cm) of the NEOSSOLO FLÚVICO Ta Eutrófico solódico gleissólico (P2), located in the Natuba River basin, Zona da Mata in Pernambuco State, Brazil. EHE = Esmectita with hydroxy between layers; Ct: = Kaolinite; Il = Illite; Qz = Quartz; Hm = Hematite; Gt = Goethite; Na = Anatase.
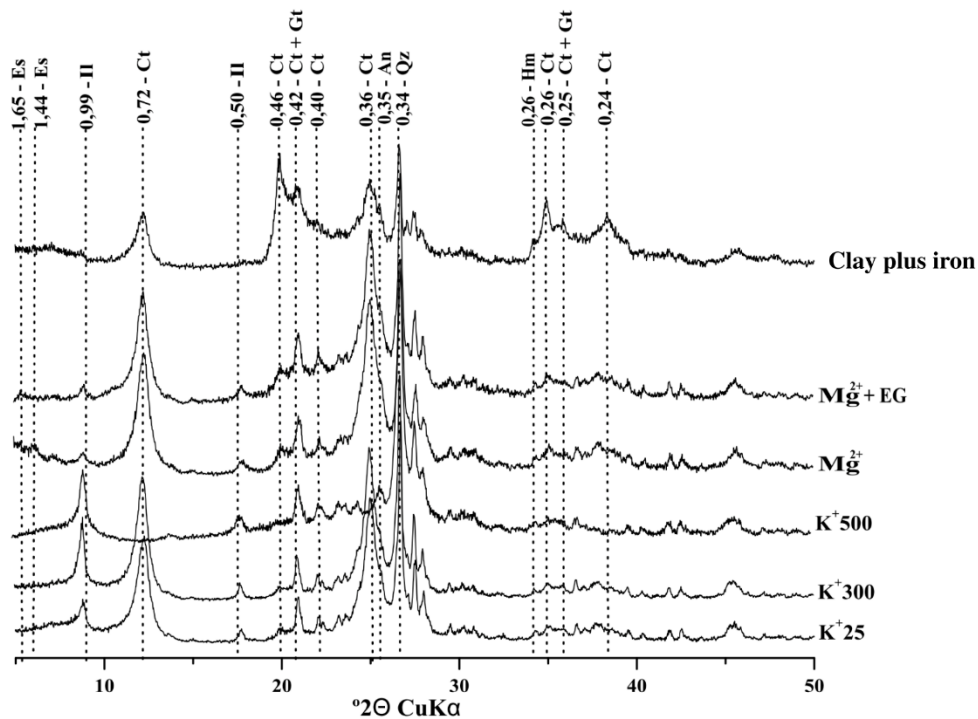
Figure 11. X-ray diffractograms of the clay fraction in the A/Cr horizon (13-30 cm) of the *NEOSSOLO LITÓLICO Distrófico fragmentário* (P12), located in the Natuba River basin, Zona da Mata in Pernambuco State, Brazil. Es = Smectite; Ct = Kaolinite; Il = Illite; Qz = Quartz; Hm = Hematite; Gt = Goethite; Na = Anatase.

Conclusions

The spectral analysis shows a high potential for characterization and classification of soils in the SiBCS. The descriptive method identified spectral patterns for different classes of soils. In the mid-IR region, the *Latossolos* and *Argissolos* presented spectral characteristics peculiar to the classification criteria. The presence of more open and shallow wave in 1624 cm^{-1} was a peculiar feature of the *Latossolos*.

The most influential attributes on the spectral behavior of the soils were organic matter, sand, clay, and iron oxides. The increased levels of organic matter and iron oxides reduced soil reflectance. The horizons with sand content above 80% exhibited strong absorption waves and strong reflectance peaks of quartz in the mid-IR region, and the waves 2681, 2600 and 2495 cm^{-1} occurred only in these horizons.

The results show the efficiency and capability of spectroradiometry for the characterization and classification of soils from the Northeast of Brazil. The accuracy and speed provided by remote sensing techniques ensured an increase in the number of observations to be analyzed, allowing soil surveys at larger scales and lower costs.

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