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Chapter 7

# Morphology, Physical and Chemical Characteristics of Mangrove Soil under Riverine and Marine Influence: A Case Study on Subaé River Basin, Bahia, Brazil

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**Abstract**

The preservation of mangrove ecosystem requires knowledge on soil Morphology, Physical and Chemical Characteristics, for understanding the requirements for their sustainability and preservation. Seven pedons of mangrove soil, five under fluvial and two under marine influence, located in the Subaé River basin were described and classified. Samples of horizons were collected for physical and chemical analyses, including Pb and Cd. The moist soils were suboxidic, with Eh below 350 mV. The pH of the pedons under fluvial influence ranged from moderately acid to alkaline, and pedons under marine influence was around 7.0. Mangrove soils under fluvial influence were characterized with the highest Pb and Cd concentrations in the pedons, which could be perhaps due to it closeness to the mining company Plumbum, while the lowest Pb concentrations was registered in the pedon furthest from the factory. Because the pedons had at least one metal above the reference level they were considered potentially toxic. The soils were classified as Gleissolos Tiomórficos Órticos (sálicos) sódico neofluvissólico, according to the Brazilian Soil Classification System and as Thiomorphic orthic Gleysol (salic) sodicluvissol (potentially toxic, very poorly drained) according with FAO. The pedon under marine influence was classified in the same subgroup, but the metal concentrations met the acceptable standard.

**Keywords:** pedogenesis, hydromorphism, heavy metals, contamination, pollution

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# 1. Introduction

## 1.1. The mangrove soils

Mangrove forests are tropical and subtropical ecosystem characterized by the presence of plant species adapted to high temperatures and organic matter content, and fluctuating salinities and oxygen conditions.

Mangroves provide ecosystem services of great social, economic and environmental importance. They are nurseries for several species of birds, fish and shellfish; they hold a complex community supporting benthic organisms that live in salt water and, they are sources of substantial part of the proteins (shellfish, crustaceans and fish) consumed or marketed by the riverside communities [1]. Despite their ecologic, social and economic functions, and benefits to coastal communities, mangroves are disappearing worldwide at the rate of 1–2% per year due to industrial development, rapid urbanization, population growth and anthropogenic activities [2].

Geology, oceanography, biology, geomorphology and pedology researchers, among others, classify the mangrove substrate as sediments or soils [3]. Hereafter, the mangrove substrate will be referred to as soil because it meets the criteria used by the Soil Survey Staff [4]. That is, they have the capacity to support life (i.e. microorganisms such as bacteria and macro organisms such as plants), filter water, recycle and purify waste and to provide food for the populations that leave riverside. Mangrove soils occur in coastal environments of tropical and subtropical regions and they are originated from sedimentary material deposited by river and marine actions or from the alteration of the sedimentary substrate (parent material). The sediments are further altered by organisms adapted to flood, anaerobic and salt conditions [3, 5–7].

Mangrove formation in different regions of the globe is related to sedimentation processes occurring in the Quaternary Period, as well as to the relative variations of sea level, in marine regressions and transgressions of the last 8–12 thousand years before the present [3, 7–9].

The textural, physical and geotechnical parameters, clay minerals, and pollen records in sediments from a paleo-delta, in southwest coast of India, throw insights on climate change and environment of deposition during the Holocene. Variations in the textural characteristics of sediments evaluated reveal a change in depositional environment of deltaic facies, apparently from marine to fluvial environment during mid-Holocene marine regression. Further, sand and silt mixture in the upper part of borehole suggests that fluvial environment was influenced by the variation in the intensity of monsoon [10].

With the end of the Holocene, the last transgression began, and the sea drowned the valleys excavated by hydrography and reworked the Pleistocene sediments forming Holocene sediments, which filled lagoons, bays and coastal strands [6]. Evaluation of major delta processes indicates that deceleration in sea-level was the key factor in Holocene delta formation [9].

Once formed, these points and islands sheltered on their inner side protected areas that from lagoons evolved to swamp areas with mangroves [8]. The sediments deposited in the marshy areas underwent to general pedogenic processes of addition, removal, transformation, translocation of

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materials and energy, and specific processes related to aggradation, salinization, gleization, sulfurization, bioturbation and paludization that result in the formation of different mangrove soils.

The local sedimentation processes depends on the geological, geomorphological, climatic and vegetation factors, quantity and quality of the mineral and organic materials fluvio-lacustre and marine deposited of each region [3]. There exist a significant interaction among highland, estuary (physiographic basin), ocean and atmosphere, as a result of local influence and environment specific factors such as climate, relief, and organisms altered formation processes. The sediments deposited in the fluvio-marine plains of calmer regions, over time transform into soils through pedogenetic process [3, 11].

Mangroves ecosystems are located in lower landscape environments. The soils formed in mangroves ecosystems are located in lower landscape because of that they are constantly receiving fluvial and marine additions of mineral and organic material to their surface (aggradation) [12]. The sediment accumulation is facilitated by vegetation, especially by mangrove species with complex root system and by flocculating salinity effect that leads to the deposition of fine clay particles carried out by rivers. The rates of sediment deposition in mangrove environments in different part of the world vary according to the characteristics of the local [13]. According to [14] it is difficult to determine the rate of mud sedimentation beneath mangroves the author observed deposition rates from 1 to 8 mm $year^{-1}$, in different regions. The more common rate of vertical accumulation is close to 5 mm $year^{-1}$ [15].

The primary contribution of the Mekong tropical delta helped to understand the stratigraphy and history of the formation of mud inland deposits on time scales of centuries and millennia [8]. The sediment accumulation ranges from 0.47 [16] to 10 cm $year^{-1}$ [8]. The energy of the rivers, ocean waves and currents, downstream relief features, root density of mangrove species, among other factors determines an uneven and unstable sedimentation pattern. The sedimentary or crystalline nature of the rocks occurring in the basins that drain the mangrove environments influence: the mineralogy and the texture of the deposited material [3]; the distribution and extension of quaternary deposits [6, 14, 17]; the distribution of the particle size of the mangrove soils [18]; and the geomorphology of the coastal region.

The frequent floods in the mangrove soils by marine salt water trigger the process of salinization. Because of the high concentrations of $Na^+$ in the marine water many mangrove soils have high rate of sodium saturation coupled with high salt concentrations [12]. Another effect of constant flooding of mangrove soil by fluvial and marine influence is the reduction of oxygen supply and high biological oxygen demand (BOD). These two factors will result in the formation of an environment with low concentration of oxygen that in turn will influence the chemistry of sulfur and iron.

Sulfates are abundant in sea water and together with Fe are important elements in the biogeochemical cycles of mangrove areas [3]. For sulfur the combination of high organic matter content, reactive Fe sources and a large quantity of sulfates, readily available, makes the mangrove soils an environment conducive to the occurrence of bacterial reduction process of sulfidization. The oscillations of redox conditions, due to seasonality, plant action, fauna or anthropogenic interventions may result in a more oxidizing condition in the soil, promoting sulfide oxidation (sulfurization) [12]. The reduction of iron forms in mangrove soils leads to

the formation of a process known as gleização [19]. Moreover, the reduction condition leads to the accumulation of organic material due to the low energy yield from the main mineralization pathway, replacing the aerobic microbial metabolism in a process called Paludization [12]. Also, variation in hydroperiod and soil moisture content affect the amount of organic matter in the sediments [20].

The high concentration of organic matter in estuarine environments is explained by factors, such as the bioturbation [12] of the local fauna and the contribution of organic material (leaf, branches and roots) from the mangrove vegetation. The concentration of C-organic tend to be higher in the first horizons where there is a greater amount of roots, algae (diatoms) and remains of animal in decomposition [21, 22]. The deposition of these materials associated with the hydromorphism reduces the rate of decomposition of the organic compounds.

### 1.2. Interaction between mangrove vegetation and soil morphological, chemical and physical characteristics

Soils of mangrove ecosystems are the result of complex interactions between abiotic factors, such as tidal oscillations and biotic factors as the activities of the species and organisms [23]. Soils provide essential nutrients for mangrove species growth and physical structure for plant anchorage and stability. They also influence wildlife conservation, and balance the environmental condition. The soil type and its morphological, physical, chemical and physicochemical characteristics are resultant of interactions between factors such as topography, climate, hydrodynamic processes, tidal margin and long-term sea level changes. Therefore, mangrove soils have a unique history in any environment [15].

Mangrove soils are generally characterized by reducing conditions and highly variable soil salinity [24, 25]. The physiographical position of mangroves within the estuary influence the soil properties (pH, Eh, electrical conductivity) and composition (clay mineralogy, organic matter and metal concentration) greatly affects soil attributes and environmental functions [26, 27]. Mangrove growth is also affected by soil texture, salinity, redox potential, and temperature [28, 29]. The texture of soils is broadly distinguished into sandy loams and silt loams, but there is great variability from one region to another.

In a mangrove environment, soils and vegetation have a strong interaction with each other, resulting both in the formation process of the former and in the characteristic of the growing environment of plants, which develop in communities directly influenced by soil characteristics. The plant species of the mangroves have their development influenced by the physical and chemical soil characteristics [30] which may compromise the growth and structure of species [31]. Texture, potential redox, pH, cation exchange capacity, organic carbon and electro conductivity can influence nutrient uptake by plants, despite the difference of selectivity of each species to remove nutrient from the same environment [32–34].

The concentration of organic matter in mangrove forest varies with the plant species age. There exist interrelationships between mangrove vegetation and soil characteristics. As the species age, the productivity and the production of litter and organic detritus that are deposited in the forest floor and within the soil profile increase [35]. After decomposition of

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the organic material the accumulation of organic matter increases. The larger organic matter content of mangrove soils influence the status of nutrient in the soil as well as pH and redox potential soils among others [35].

On the other hand, the distribution of mangrove species along the coast has been attributed to: the eco-physiological response of plants to one or more series of environmental gradients; the combination of factors such as frequency and duration of flooding, substrate flooding, pore water salinity and pore water potential [14] and; the change in the environment deposition during the Holocene, and to neotectonic factors, such as changes in sea level and varied intensity of the southwestern monsoon [10]. Due to this strong interaction and specificities of the estuarine environment, mangroves are considered fragile ecosystems, highly sensitive to changes in the environment, mainly due to anthropic actions, which tend to disrupt the system by modifying the environment.

There are about 50 species of mangroves found in the world adapted to tidal oscillations, temperature, salinity and soil texture. The mangrove species most commonly found are *Rhizophora mangle* (red mangrove), identified by the tangle of aerial roots that promote the exchange of oxygen, *Avicennia germinans* (black mangrove), identified by projections called pneumatophores, projected in the soil surrounding the trunk of the tree and *Laguncularia racemosa* (white mangrove) species that projects salts in its leaves. These species may present high growth rates in soils without nutritional limitations [36]. There is a relationship between the soil characteristics and mangrove species [25, 37]. For instance, *Rhizophora* is found in environments with a more alkaline pH, as well as high levels of N, P and C; *Laguncularia* in soils with sandy loamy texture; and *Avicennia germinans* in environments with lower tidal influence.

As upland soils, the evaluation of mangrove soils may provide suitable indicators of the macrofaunal and nutrient status [38, 39] as well as the effect of anthropogenic impact as indicated by the presence of organic and inorganic contaminants.

### 1.3. Impact of anthropogenic activities on mangrove

In spite of the increased awareness of the value and significance, the mangroves are threatened worldwide by the risk of disappearing, due to economic and social pressure.

Given the importance of mangrove forests and the impacts of global climate change and anthropogenic activities on this ecosystem, mangroves should be legally protected however, less than 10% fall into this category [40, 41]. According to the Brazilian Law No. 12.727/2012 of the Forest Code [42] classifies the mangrove forests as Areas of Permanent Preservation. In general, the destruction of these forests is linked to anthropic interests, activities and needs such as industrial demand, population growth, or poor coastal management, which reflect the alteration, degradation and loss of the natural habitat of several species [43].

Uncontrolled industrialization and urbanization in coastal regions, has damaged the mangrove ecosystem threaten biodiversity, human health [44, 45] and marine life. Heavy metals are considered as anthropogenic pollutants of great impact on mangrove ecosystems [46]. The effect of heavy metals in mangrove environments is worrying because these ecosystems are a nursery for several species (e.g. fish, crabs, oysters), which are consumed and marketed by

the riverine population. In Brazil and in the world, the effect of metals has been reported on soils, plant species and animals of mangroves [11, 41, 47]. Oil spill can cause lethal impacts to plants by preventing transport of oxygen [48]. Enterprises and activities associated with these pollutants have been observed located closer to mangroves, becoming potential threatening ecosystems [46].

Because they are in environments bordering large human settlements, mangroves are under great pressure of use and occupation across the globe. In addition to being exploited, without a rational system of use and management, plants and animals are collected for different purposes. In addition to that, the mangrove directly affected by: the discharge of solid and liquid wastes from the cities that border the rivers and drain their waters to the sea; and by the disorderly occupation of people who drain and bury the mangrove for expansion of urban centers. In the municipality of Santo Amaro, Bahia, Brazil, in addition to all the previously related problems, the mangroves were contaminated by waste from Pb processing in a factory located on the banks of the Subaé River.

## 2. Study of case: mangrove soil contamination from lead processing industry

Industrial activities are known for the deleterious effects on mangroves, particularly for the presence of high concentrations of toxic elements such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and zinc (Zn) that cause adverse effects to fauna and flora of mangrove forests, directly or indirectly affecting human health.

Negative effects of the presence of toxic elements from industrial activities in mangroves have been reported [11], due to galena processing activities in the municipality of Santo Amaro-Bahia. The mining-metallurgical complex installed in 1960, 2.5 km Northwest of the city for the production of lead alloys (Pb), in addition to atmospheric contamination, left a liability of around 500 thousand tons of slag (21% Cd and up to 3% of Pb) that resulted in the contamination of the Subaé River and its estuary due to overflow of the tailings pond.

It is believed that Santo Amaro has the highest urban lead contamination in the world, with serious effects on human health, as indicated by the incidence of metal-induced diseases in the population and by the environment contamination.

Studies indicate that the presence of heavy metals in the mangroves of the Subaé River Basin cause social, economic and health impacts, as the ecosystem is a source of subsistence and income for riverside residents, who may be consuming contaminated fish [49, 50]. Negative effects on the mangroves of Santo Amaro and São Francisco do Conde were reported by [11], which is presented in this study of case. The study characterized and classified mangrove soils from Subaé Basin and evaluated the Pb and Cd distribution in horizons of mangrove.

### 2.1. Materials and methods

The mangroves evaluated in this study are located in the Subáe Basin, Bahia, Brazil, in the municipalities of Santo Amaro and São Francisco do Conde (**Figure 1**). The Subaé River basin

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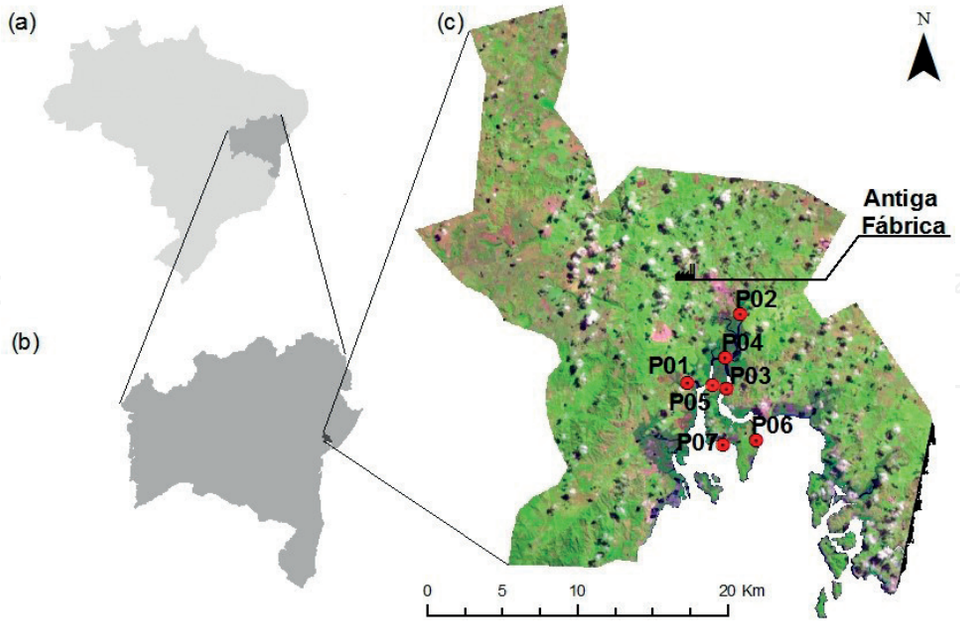



**Figure 1.** Location of the estuarine zone of the Subaé river, Bahia, Brazil. (a) Location of Santo Amaro in the Brazilian region. (b) Study area in Santo Amaro. (c) Location of the pedons.

is a part of the river basin complex "Recôncavo Norte", located in Northeastern of Bahia, with a total area of 18,015 km$^2$. This area is drained, aside from the Subaé River, by: Subaúma, Catu, Sauípe, Pojuca, Jacuípe, Joanes, Açu and the secondary rivers from "Baia de todos os Santos" (BTS) and the Inhambupe River [51].

The regional climate is Af (tropical rain forest climate), according to Köppen's classification, i.e., tropical humid to sub-humid and dry to subhumid, with average annual temperature of 25.4°C (maximum average of 31°C and minimum of 21.9°C) and annual average rainfall varying from 1000 to 1700 mm in the rainiest months and from 60 to 100 mm in the driest months [52]. About 2/3 of the territory of Santo Amaro has smooth, wavy relief, coastal plateau, marine and fluvial marine waters.

The region of study is in the Northeaster face from San Francisco craton (Recôncavo Sedimentary Basin), of Meso-Cenozoic age, delimited by a subparallel system of normal faults. The geology of the area is composed by rocks of the following groups: Santo Amaro (Candeias formation: interleaved shale and silt, with levels of limestone and dolomite, sandstone); Island Islands (interleaved shale and sandstone, loam, calciferous sandstone, carbonaceous shale, silicon and calcilutite); and Brotas (Sergi Formation: fine sandstone to conglomerate, conglomerate and subordinate pellet), as well as reservoirs of marshes and mangroves [53].

The sample area mangrove areas, there is a predominance of Vertisols, Argisols, Neosols, in addition to Gleysols [54] are class of soil prevailing in the area. The plant species found in the study area are: *Rhizophora mangle* (Red mangrove, RM), *Laguncularia racemosa* (white mangrove, WM) and *Avicennia schaueriana* (black mangrove, BM). The sample location, the profile code, the prevailing vegetation and the geographical coordinates are shown in **Table 1**.

| Mangrove | Identification | Vegetation | Latitude | Longitude |
|---|---|---|---|---|
| Santo Amaro | P1 | WM | 0533387 N | 8,610,674 E |
| São Brás | P2 | WM and RM | 0529852 N | 8,606,114 E |
| São Bento das Lajes | P3 | RM and WM | 0532483 N | 8,605,736 E |
| Santo Amaro | P4 | RM and WM | 0532395 N | 8,607,834 E |
| Santo Amaro | P5 | RM, WM and BM | 0531579 N | 8,605,970 E |
| Ilha Cajaíba | P6 | RM and BM | 0534697 N | 8,602,227 E |
| Ilha de Araçá | P7 | WM and BM | 0532211 N | 8,601,506 E |

**Table 1.** Geographic coordinates of the profiles and respective vegetation predominant along the Subaé Basin.

## 2.2. Soil sampling

Based on aerial photography data, the closeness to the factory, field observation, tide tables, and information provided by local fishermen, seven pedons (P) were selected and sampled, of which five pedons represented the fluvial lowland of the Subaé River (P1 to P5) in higher areas and 2 of them in lower areas, closer to the sea (P6 and P7) (**Figure 1**). The pedons P1, P3, P4, P5 and P6 are located at Cajaíba island, which divides the Subaé River into two branches near its mouth, in an anthropic undisturbed environment (P7) as compared with the mangrove forest along the river banks on the continent; and one pedon in the neighboring area of the former Plumbum Mining (P2).

The sites for vertical cuts of soils were defined by following the tide table: when the tide is low, some fluvial dams are formed on the river banks, which enabled the morphological description of profiles and the sampling process, carried out according to [55]. After describing the profiles horizon and layer samples were collected, stored in plastic bags, and maintained in a cold chamber at 4°C, for subsequent chemical and physical analyses.

## 2.3. Analytical procedures

### *2.3.1. Oxidation and reduction potential and pH measurements*

The oxi-reduction potential (Eh) and pH level of all pedon horizons and layers were measured in the field. The Eh readings (Hanna HI 8424) were obtained by using a platinum electrode and corrected by adding potential of the calomelane reference electrode (+244 mV) and the pH levels were measured with a glass electrode, which was previously calibrated with standard pH solutions at 4.0 and 7.0, after balancing samples and electrodes.

### *2.3.2. Laboratory*

Soil samples were air-dried, around 35°C, crumbled, and ground with a soil hammer mill, using a 2 mm sieve, to obtain air-dried fine soil.

For texture test, soluble salts were previously removed with 60% ethylic alcohol and organic matter by hydrogen peroxide. The pipette method was used with some modifications: 20 g

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of sample was dispersed in 100 mL of water and 10 mL of 1 mol $L^{-1}$ sodium hexametaphosphate [56]. After that samples were kept overnight to settle down in bottom, the samples were shaken for 16 h at 30 rpm in a Wagner agitator, model TE-161, following the other procedures of the method. The samples were assessed to the following chemical properties: electrical conductivity (EC) in the saturation extract; pH in water (1:2.5 soil:solution ratio); exchangeable $Ca^{2+}$, $Mg^{2+}$ and $Al^{3+}$, through titration after extraction with a 1 mol $L^{-1}$ KCl solution; Na and K by flame photometry, following extraction through Mehlich-1; H + Al extracted through 0.5 mol $L^{-1}$ calcium acetate at pH 7.0, and determined with 0.025 mol $L^{-1}$ NaOH. Based on the obtained data, it was calculated the sum of bases (S), cation exchange capacity (CEC), and base saturation (V). The phosphorus content was determined by photocolorimetry. All determinations were carried out as described by [56]. Organic carbon was determined by the dry method (muffle) for classification according to [57]. The sulfur content was determined by sample digestion with HCl 1:1, and then calculated by gravimetry after precipitation with $BaCl_2$ [56]. In order to assess the existence of thionic sulfur in the soil, a 0.01 m soil layer, at field capacity, was incubated at room temperature for 8 weeks. Soils with ΔpH [pH(KCl) − pH($H_2O$)] values lower than 0.5 units after incubation were considered thionic [57].

Metals were extracted and determined by method 3050B [58], by which 0.5 g of the dry soil fraction was ground in an agate mortar and digested in 10 mL of a $HNO_3$:$H_2O$ deionized solution, at a 1:1 proportion, with addition of 10 mL $H_2O_2$ for organic matter oxidation, in a digestion block heated to 95 ± 5°C for about 2 h. Samples were cooled for 15 min, then 5 mL of a $HNO_3$ solution was added again. To complete digestion, 5 mL of concentrated HCl and 10 mL of deionized $H_2O$ were also added. After digestion, the samples were cooled, filtered, completed to 50 mL and the metals Pb and Cd, determined with an atomic absorption spectrophotometer (model AAS Varian AA 220 FS).

*2.3.3. Soil classification*

Based on the morphological description and the analytical results, pedons were classified according to the Brazilian System of Soil Classification (SiBCS) [57], the U.S. Soil Taxonomy [54], and the World Reference Base for Soil Resources [59].

## 3. Results and discussion

The results of morphological and physical analyses of pedons located on a plain relief, directly exposed to tides, under fluvial (P1 to P5) and marine (P6 and P7) influence, from fluvial-maritime sediments, deposited on a sediment rocky mineral (shale), are shown in **Table 2**.

The seven pedons are poorly drained, due to constant flooding by the tide, and, under anaerobiose conditions, they favor the waterlogging process, which affects the removal, translocation, and transformation processes of Fe compounds, resulting in bluish and greenish colors, with red or yellowish mottles in horizons and layers (**Table 2**).

Generally, Gleysols have a massive structure, identified in all horizons and layers of the pedons under study (**Table 2**). Although the consistency was not measured in the field, the flooding condition resulted in very or extremely hard soils when dry. The transition between horizons was

| Horizons | Depth | Color | | Structure | Transition | Texture class[1] | Sand | Silt | Clay |
|---|---|---|---|---|---|---|---|---|---|
| | cm | Hue | Mottle | | | | g kg$^{-1}$ | | |
| **P1—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | |
| Agn | 0–8 | Gley 1–10 GY 4/1 | 7. 5 YR 5/6 | Massif | Flat and diffuse | Very clayey | 16 | 196 | 788 |
| 2Agn | 8–20 | Gley 1–10 GY 4/1 | 7.5 YR 5/6 | Massif | Flat and diffuse | Very clayey | 29 | 192 | 778 |
| 3Agn | 20–34 | Gley 1–10 GY 4/1 | 7.5 YR 5/6 | Massif | Flat and diffuse | Very clayey | 39 | 122 | 839 |
| 4Agn | 34–55 | Gley 1–10 GY 4/1 | — | Massif | Flat and diffuse | Very clayey | 66 | 102 | 832 |
| **P2—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | |
| Agn | 0–20 | Gley 1 10Y 2.5/1 | 10YR 4/6 | Massif | Flat and diffuse | Medium | 459 | 208 | 333 |
| 2Agn | 20–32 | Gley 1 10Y 2.5/1 | — | Massif | Flat and diffuse | Medium | 476 | 213 | 311 |
| 3Agn | 32–61 | Gley 1 10Y 3/1 | — | Massif | Flat and diffuse | Medium | 494 | 185 | 321 |
| 4Agn | 61–83 | Gley 1 10Y 4/1 | — | Massif | Flat and diffuse | Medium | 383 | 295 | 322 |
| 5Agn | 83–102 | — | — | Massif | — | Clayey | 308 | 271 | 421 |
| **P3—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | |
| Agn | 0–5 | Gley 1 5G 4/1 | 2.5YR 4/8 | Massif | Flat and diffuse | Medium | 477 | 254 | 270 |
| 2Agn | 5–25 | Gley 1 5G 4/1 | — | Massif | Flat and diffuse | Medium | 609 | 86 | 305 |
| 3Agn | 25–49 | Gley 1 5GY 4/1 | 10 YR 3/6 | Massif | Flat and diffuse | Clayey | 486 | 124 | 390 |
| 4Agn | 49–71 | Gley 1 5G 4/1 | — | Massif | — | Clayey | 439 | 209 | 352 |
| **P4—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | |
| Agn | 0–7 | Gley 1 5G 3/1 | Gley 1 5G 2.5 /1 and 7.5 YR 4/6 | Massif | Flat and clear | Medium | 666 | 78 | 255 |
| 2Agnj | 7–18 | Gley 2 10B 3/1 | 10B 4/1 | Massif | Flat and clear | Medium | 378 | 419 | 203 |

| Horizons | Depth | Color | | Structure | Transition | Texture class[1] | Sand | Silt | Clay |
|---|---|---|---|---|---|---|---|---|---|
| | cm | Hue | Mottle | | | | g kg$^{-1}$ | | |
| 3Agnj | 18–41 | Gley 1 5G 5/1 | Gley 2 10GB 4/1 and Gley 1 5G 6/2 | Massif | Flat and clear | Sandy | 910 | 3 | 88 |
| 4Agnj | 41–60 | Gley 1 5G 4/1 | — | Massif | Wavy and abrupt | Medium | 688 | 63 | 249 |
| 4Crgnj | 60–70 | Gley 1 10GY 3/1 | 2.5 YR 2.5/4 | — | — | Medium | 648 | 109 | 244 |
| **P5—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | |
| Agn | 0–15 | Gley 1 5G 4/1 | 5YR 4/6 | Massif | Flat and gradual. | Very Clayey | 26 | 150 | 824 |
| 2Agn | 15–26 | Gley 2 10B 4/1 | 5YR 4/6 | Massif | Flat and gradual | Very Clayey | 27 | 233 | 740 |
| 3Agn | 26–43 | Gley 2 10B 3/1 | — | Massif | Irregular and Abrupt | Very Clayey | 27 | 38 | 935 |
| 4Agn | 43–60 | Gley 2 5 PB 5/1 | — | Massif | Irregular and Abrupt | Medium | 269 | 677 | 54 |
| 4Crgn | 60–70 | Gley 1 5G 5/2 | — | Massif | — | Clayey | 211 | 238 | 551 |
| **P6—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | |
| Agn | 0–15 | Gley 1 5GY 3/1 | 7YR 3/3 | Massif | Flat and diffuse | Medium | 439 | 458 | 103 |
| 2Agn | 15–33 | Gley 1 10Y 3/1 | — | Massif | Flat and diffuse | Silty | 86 | 828 | 86 |
| 3Agn | 33–48 | Gley 1 5G 3/1 | — | Massif | Flat and clear | Very clayey | 119 | 272 | 609 |
| 4Agn | 48–60 | Gley 1 5G 4/1 | — | Massif | — | Very clayey | 315 | 27 | 659 |
| **P7—Gleysol thiomorphic orthic (salic) sodic luvissol, very poorly drained** | | | | | | | | | |
| Agn | 0–9 | Gley 1 10Y 3/1 | 7YR 3/3 | Massif | Flat and diffuse | Medium | 321 | 637 | 42 |
| 2Agn | 9–17 | Gley 1 10Y 4/1 | — | Massif | Flat and diffuse | Medium | 291 | 686 | 24 |
| 2Crgn | 17–28 | Gley 1 10Y 4/1 | — | Massif | Flat and abrupt | Silty | 100 | 836 | 64 |

[1]Classification according to Embrapa [57].

**Table 2.** Morphological properties and physical attributes of pedons from mangrove soils in the Subaé river basin, Santo Amaro, Bahia, Brazil.

flat and diffuse (P1, P2, P3, P4, P6, and P7) or gradual (P5), showing sedimentation with layers consisting of material with similar composition and homogenized by the action of organisms.

In mangroves, there is a constant sedimentation of fine dust (silt and clay) brought by tidal variation, which may be explained by the low-energy environment [60]. Texture varied from medium to very clayey, with a predominance of the finer over the sandy fraction (**Table 2**). Also, irregular variation of texture between the soil horizons and layers, in all pedons, indicates major changes in the environmental conditions of the system [61]. Clay in the pedons ranged from 2.4 to 93.5%, showing wide texture variability, to, is a characteristic of mangrove soils [21]. In most horizons and layers from P1 to P5, the pedons influenced by the river, there is a prevalence of the clay fraction, while in the pedons influenced by the sea, P6 and P7, silt and clay are predominant.

### 3.1. Pedons formed under fluvial influence

From the pedons under fluvial influence, P1 located on the edge of the mangrove of the sampled region was shallowest (0.55 m). All horizons and layers had a 1 10GY Gley color, which indicates a flooded environment and oxidation process promoted by roots and soil microorganisms. Along P1, a more homogenous texture distribution was observed when compared to the other pedons, which may be related to the fact of being in a zone with lower fluvial influence, on the riverbank (continent); therefore, in a more protected environment (**Table 2**).

The deepest pedon was P2 (1.02 m), due to its location at a higher position, so that it is not completely flooded for a long time. The layers and horizons of this pedon had a 1 10Y Gley color in the whole profile, due to its continuous drying cycles, as well as the presence of very fine to thick roots, up to the horizon 5 Agn. The horizon textures of this pedon were medium, and the last was the most clayey, possibly indicating accumulation of particulate material in the aforementioned horizons (**Table 2**).

The pedons P3, P4, and P5 have similar depths (around 0.70 m), with colors varying from 1 5G 4/1 Gley to 2 10B 4/1 Gley and a texture ranging from medium (P3 and P4) to very clayey (P5), indicating pedons formed in accumulation and storage regions, respectively. In P4, a horizon (4 Agnj) with shell deposition was found, attributed to two possible causes: presence of oysters that use the stem and roots of the plant species *Rhizophora mangle* (predominating in the area) as habitat and fall on the ground and are incorporated with time; or as a shell disposal area for the fishermen, still on site, as a result of shell fishing (information provided by local fishermen).

The sequence of Ag horizons or layers was identified in P1, P2, and P3 and the Agr sequence in P4 and P5, with material discontinuity (fluvial nature), evidenced by stratifications, with an irregular texture variation (**Table 2**) and in-depth organic C content, found in all pedons, indicating fluvial sediment storage [59]. In these soils, there are moderate a horizons and the Cr layer of P4 and P5 corresponds to a soft rocky mineral, derived from blue-greenish shales of the island group, also called "green rust" [62].

### 3.2. Pedons formed under marine influence

Pedons formed under marine were shallower than those formed under fluvial influence (**Table 2**), which is related to a longer submersion time and the location in a marine estuary,

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favoring greater particle removal. This behavior is very clear in P7, located in the southern part of the island, in the mouth of "Baía de Todos os Santos", where parental material is almost exposed, in addition to sparse or almost absent presence of vegetation.

Dark brown mottles (7YR 3/3) of horizons Agn of P6 and P7 occur due to oxidation of reduced Fe forms in microenvironments created by roots and soil biota [61, 63]. The texture of these pedons ranged from medium in the surface to very clayey, indicating an alternation of different materials deposited over time (**Table 2**). In P7, high silt percentage may be related to the greater particle deposition in the area, the scarce presence or absence of vegetation, and presence of soft rock at a depth of 0.17 m. The sequence of Agn horizons or layers was identified in P6 and Agn-Crg in P7, for the same reasons as explained for pedons under fluvial influence.

### 3.3. Chemical properties

The results of chemical analyses of pedons under fluvial (P1–P5) and marine (P6 and P7) influence are shown in the **Tables 3** and **4**. Of the seven pedons, four had only an A horizon (P1–P3, and P6) and three had an A horizon and a C layer (P4, P5, and P7). All pedons are formed by a gley horizon, or a reductive environment, due to tidal movements that maintain the soil waterlogged most of the time.

| Profile | Depth | S | pH ($H_2O$) | pH incubation levels[1] | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | cm | (%) | | 0[2] | 15 | 30 days | 45 | 60 | ΔpH[3] |
| **P1—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | |
| Agn | 0–8 | 3.6 | 6.7 | 6.3 | 6.3 | 6.6 | 6.8 | 4.9 | 1.4 |
| 2Abgnj | 8–20 | 3.6 | 6.4 | 7.1 | 4.0 | 3.3 | 3.1 | 2.5 | 4.6 |
| 3Abgnj | 20–34 | 3.5 | 6.2 | 7.1 | 3.1 | 3.1 | 2.9 | 2.6 | 4.5 |
| 4Abgnj | 34–55 | 3.7 | 6.1 | 8.1 | 4.2 | 3.9 | 3.3 | 3.1 | 5.0 |
| **P2—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | |
| Agnj | 0–20 | 3.8 | 5.8 | 6.3 | 5.0 | 3.7 | 2.7 | 3.0 | 3.3 |
| 2Agnj | 20–32 | 3.6 | 6.0 | 6.1 | 3.1 | 2.4 | 1.7 | 2.2 | 3.9 |
| 3Agnj | 32–61 | 3.8 | 5.9 | 7.0 | 3.0 | 2.2 | 2.1 | 2.3 | 4.7 |
| 4Agn | 61–83 | 3.6 | 6.5 | 7.5 | — | — | — | — | — |
| 5Agn | 83–102+ | 3.8 | 7.0 | 7.5 | — | — | — | — | — |
| **P3—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | |
| Agnj | 0–5 | 4.0 | 6.0 | 7.0 | 3.7 | 2.9 | 2.6 | 2.4 | 4.6 |
| 2Agnj | 5–25 | 3.9 | 4.7 | 6.1 | 3.4 | 3.1 | 3.0 | 2.9 | 3.2 |
| 3Agnj | 25–49 | 3.8 | 5.8 | 7.0 | 3.0 | 2.4 | 2.4 | 2.3 | 4.7 |
| 4Agnj | 49–71+ | 3.7 | 6.4 | 7.5 | 3.4 | 2.5 | 2.6 | 2.3 | 5.2 |
| **P4—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | |
| Agn | 0–7 | 3.8 | 6.4 | 6.6 | 5.8 | 5.4 | 4.7 | 4.2 | 2.4 |
| 2Agnj | 7–18 | 3.8 | 4.7 | 6.6 | 3.1 | 2.4 | 1.7 | 2.3 | 4.3 |

| Profile | Depth | S | pH ($H_2O$) | pH incubation levels[1] | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | cm | (%) | | 0[2] | 15 | 30 days | 45 | 60 | ΔpH[3] |
| 3Agnj | 18–41 | 3.9 | 5.8 | 6.9 | 3.5 | 2.4 | 2.2 | 2.2 | 4.7 |
| 4Agnj | 41–60 | 3.9 | 4.9 | 7.0 | 3.0 | 2.4 | 2.2 | 2.4 | 4.6 |
| 4Crgnj | 60–70 | 3.7 | 3.6 | 6.9 | 2.8 | 2.5 | 2.0 | 2.3 | 4.6 |
| **P5—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | |
| Agn | 0–15 | 3.8 | 6.6 | 6.2 | 6.5 | 6.3 | 6.4 | 6.4 | −0.2 |
| 2Agnj | 15–26 | 3.8 | 5.5 | 6.3 | 3.4 | 2.9 | 2.7 | 2.7 | 3.6 |
| 3Agnj | 26–43 | 3.4 | 5.4 | 6.7 | 3.0 | 2.8 | 2.6 | 2.4 | 4.3 |
| 4Agn | 43–60 | 3.7 | 7.4 | 7.1 | 7.0 | 6.6 | 6.4 | 7.3 | −0.2 |
| 4Crgn | 60–70+ | 3.7 | 7.6 | 7.8 | 7.5 | 6.4 | 7.3 | 7.4 | 0.4 |
| **P6—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | |
| Agnj | 0–15 | 3.3 | 5.8 | 7.2 | 4.0 | 3.1 | 3.2 | 3.0 | 4.2 |
| 2Agnj | 15–33 | 3.4 | 6.5 | 7.1 | 3.6 | 3.4 | 3.7 | 3.0 | 4.1 |
| 3Agnj | 33–48 | 3.3 | 5.5 | 7.3 | 3.1 | 3.0 | 1.7 | 2.3 | 5.0 |
| 4Agn | 48–60 | 3.3 | 5.3 | 7.2 | — | — | — | — | — |
| **P7—Gleysol thiomorphic orthic (salic) sodic luvissol, very poorly drained** | | | | | | | | | |
| Agnj | 0–9 | 3.9 | 7.3 | 7.3 | 6.6 | 5.7 | 5.9 | 2.9 | 4.4 |
| 2Agn | 9–17 | 3.8 | 7.2 | 7.4 | 6.7 | 6.4 | 7.0 | 7.1 | 0.3 |
| 2Crgn | 17–28 | 3.6 | 7.0 | 7.1 | 6.6 | 6.6 | 7.0 | 7.0 | 0.1 |

[1]Sixty-day incubation.

[2]It corresponds to pH value on site, humid sample.

[3]It corresponds to the difference between pH level in the beginning (0) and in the end (60 days).

**Table 3.** Values for sulfur (S%), $pH_{H_2O,}$ and $pH_{incubation}$ of mangrove soils in the Subaé river basin, Santo Amaro, Bahia, Brazil.

The thiomorphic nature of profiles or layers is determined by the ΔpH value after soil incubation, and soils with ΔpH values >0.5 are identified this way, observed for most of the layers, except for the horizons Agn and 4Agn of P5 and 2 Agn and 2 Crgn of P7. The results for the thiomorphic nature are according to the total S content, higher than the minimum content required (0.75%) to characterize the presence of sulfide materials [64], ranging from 3.3 (2Agnj of P6) to 4.0% (Agnj of P3) (**Table 3**), which is normal for mangrove soils [65, 66].

Organic C contents in pedons formed under fluvial influence (P1, P2, P3, P4, and P5) ranged from 47.0 in the 4 Agn horizon in P2 to 53.4 g $kg^{-1}$ of 4 Agn in P5, with higher nominal values than those of soils formed under tidal influence (45.7 in the 2Crgn layer of P7 at 51.7 g $kg^{-1}$ in the 3 Agn of P6 and Agn horizons of P7) (**Table 4**). However, for both environments, pedons were classified as orthic, because the organic C content was below 80 g $kg^{-1}$.

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In all pedons, percentage of sodium saturation (PST) values (**Table 4**) (47% in the 2 Agnj horizon of P4 at 69% in the Agn horizon of P1) exceeded the threshold values that classify a soil as sodic

| Horizons/layers | Depth | CE | Ca | Mg | Al | H + Al | Na | K | SB | T | V | PST | P | C.org. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | cm | dS $m^{-1}$ | $cmol_c\ kg^{-1}$ | | | | | | | | % | | mg $kg^{-1}$ | g $kg^{-1}$ |
| **P1—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | | | | | | |
| Agn | 0–8 | 40 | 3.0 | 14.0 | 0.2 | 3.0 | 51.2 | 3.6 | 71.7 | 75 | 96 | 69 | 5.3 | 48.8 |
| 2Agn | 8–20 | 38 | 3.8 | 15.6 | 0.2 | 4.8 | 52.3 | 3.3 | 74.8 | 80 | 94 | 66 | 5.5 | 49.8 |
| 3Agn | 20–34 | 36 | 3.6 | 16.9 | 0.2 | 5.6 | 55.5 | 3.4 | 79.4 | 85 | 93 | 65 | 5.7 | 51.6 |
| 4Agn | 34–55 | 42 | 4.5 | 15.5 | 0.2 | 7.1 | 49.0 | 4.0 | 73.1 | 80 | 91 | 61 | 4.9 | 50.2 |
| **P2—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | | | | | | |
| Agn | 0–20 | 35 | 2.1 | 7.6 | 0.1 | 5.4 | 14.9 | 1.2 | 25.9 | 31 | 83 | 48 | 5.2 | 50.6 |
| 2Agn | 20–32 | 35 | 4.5 | 4.3 | 0.1 | 5.3 | 19.2 | 1.2 | 29.2 | 35 | 85 | 56 | 5.1 | 54.0 |
| 3Agn | 32–61 | 33 | 3.2 | 6.7 | 0.1 | 4.6 | 16.4 | 1.2 | 27.5 | 32 | 86 | 51 | 5.2 | 51.0 |
| 4Agn | 61–83 | 31 | 2.5 | 10.0 | 0.1 | 1.4 | 18.1 | 1.9 | 32.6 | 34 | 96 | 53 | 5.2 | 49.6 |
| 5Agn | 83–102+ | 22 | 3.7 | 9.6 | 0.0 | 1.8 | 16.0 | 2.0 | 31.3 | 33 | 95 | 48 | 5.4 | 53.4 |
| **P3–Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | | | | | | |
| Agn | 0–5 | 36 | 2.7 | 8.4 | 0.0 | 1.9 | 22.4 | 1.4 | 34.8 | 37 | 95 | 61 | 5.1 | 50.7 |
| 2Agn | 5–25 | 43 | 2.5 | 8.0 | 0.0 | 8.8 | 27.7 | 1.1 | 39.4 | 48 | 82 | 58 | 5.0 | 51.0 |
| 3Agn | 25–49 | 44 | 3.3 | 10.8 | 0.0 | 7.1 | 35.2 | 1.6 | 50.8 | 58 | 88 | 61 | 4.9 | 53.0 |
| 4Agn | 49–71+ | 38 | 3.5 | 11.3 | 0.1 | 5.3 | 39.5 | 2.0 | 56.2 | 61 | 91 | 64 | 5.4 | 51.9 |
| **P4—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | | | | | | |
| Agn | 0–7 | 31 | 1.5 | 5.3 | 0.0 | 2.6 | 18.1 | 1.1 | 26.0 | 29 | 91 | 63 | 5.1 | 51.6 |
| 2Agnj | 7–18 | 27 | 1.6 | 4.2 | 0.7 | 6.1 | 11.7 | 1.1 | 18.7 | 25 | 75 | 47 | 5.1 | 52.1 |
| 3Agnj | 18–41 | 30 | 2.2 | 4.6 | 0.0 | 4.3 | 12.8 | 1.2 | 20.8 | 25 | 83 | 51 | 5.3 | 52.9 |
| 4Agnj | 41–60 | 29 | 2.3 | 7.4 | 0.5 | 6.7 | 19.2 | 2.2 | 31.0 | 38 | 82 | 51 | 5.1 | 53.1 |
| 4Crgnj | 60–70 | 29 | 7.8 | 4.6 | 3.3 | 12.3 | 51.2 | 1.1 | 64.7 | 77 | 84 | 66 | 5.1 | 50.1 |
| **P5—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | | | | | | |
| Agn | 0–15 | 28 | 2.9 | 14.1 | 0.1 | 3.6 | 56.5 | 3.4 | 76.9 | 81 | 96 | 70 | 5.2 | 53.1 |
| 2Agn | 15–26 | 20 | 3.5 | 14.7 | 0.2 | 7.2 | 42.7 | 4.8 | 65.7 | 73 | 90 | 59 | 5.4 | 50.2 |
| 3Agn | 26–43 | 38 | 5.1 | 13.0 | 0.3 | 11.1 | 59.7 | 4.8 | 82.7 | 94 | 88 | 64 | 5.3 | 52.4 |
| 4Agn | 43–60 | 44 | 8.6 | 9.8 | 0.1 | 0.9 | 43.7 | 2.2 | 64.3 | 65 | 99 | 67 | 5.6 | 47.0 |
| 4Crgn | 60–70+ | 33 | 4.9 | 10.1 | 0.1 | 1.0 | 20.3 | 3.3 | 38.5 | 40 | 97 | 51 | 6.2 | 52.7 |
| **P6—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | | | | | | | | | | |
| Agn | 0–15 | 36 | 3.4 | 11.3 | 0.1 | 6.3 | 38.4 | 3.1 | 56.1 | 62 | 90 | 62 | 5.7 | 46.6 |

| Horizons/layers | Depth | CE | Ca | Mg | Al | H + Al | Na | K | SB | T | V | PST | P | C.org. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | cm | dS $m^{-1}$ | $cmol_c\ kg^{-1}$ | | | | | | | | % | | mg $kg^{-1}$ | g $kg^{-1}$ |
| 2Agn | 15–33 | 46 | 6.3 | 16.2 | 0.1 | 5.6 | 58.7 | 4.2 | 85.4 | 91 | 94 | 64 | 5.1 | 48.5 |
| 3Agn | 33–48 | 41 | 5.4 | 19.6 | 0.6 | 10.9 | 70.4 | 4.5 | 99.9 | 111 | 90 | 64 | 5.4 | 51.7 |
| 4Agn | 48–60 | 57 | 5.5 | 11.6 | 0.1 | 3.7 | 71.5 | 5.4 | 94.0 | 98 | 96 | 73 | 5.2 | 50.2 |
| **P7—Gleysol thiomorphic orthic (salic) sodic luvissol, very poorly drained** | | | | | | | | | | | | | | |
| Agn | 0–9 | 45 | 4.5 | 12.8 | 0.2 | 2.2 | 54.4 | 3.1 | 74.9 | 77 | 97 | 71 | 7.1 | 51.7 |
| 2Agn | 9–17 | 48 | 5.5 | 10.7 | 0.2 | 1.9 | 58.7 | 3.0 | 77.7 | 80 | 98 | 74 | 5.3 | 48.7 |
| 2Crgn | 17–28 | 42 | 7.5 | 15.7 | 0.2 | 2.1 | 67.2 | 2.8 | 93.2 | 95 | 98 | 71 | 5.7 | 45.7 |

**Table 4.** Chemical attributes of pedons in the mangrove in the Subaé river basin, Santo Amaro, Bahia, Brazil.

(PST ≥ 6), which results in clay dispersion and, probably, in soil organic matter dispersion. High $Na^+$ levels in all pedons, associated with high pH levels, contribute to the halomorphism processes. Excessive salts in the layers or horizons whose EC values ranged from 20 dS $m^{-1}$ (2 Agn of P5) to 57 dS $m^{-1}$ (3 Agn of P6) led to the classification of pedons as salic, since these values are much higher than the threshold values to classify soils as salic (EC ≥ 7 dS $m^{-1}$) [57] (**Table 4**). The salic nature hinders water absorption by terrestrial plants, but is less relevant for mangrove plants that are adapted to EC levels exceeding those of the classification.

Sorption complex of pedons is dominated by cations $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ and, in almost all horizons and layers, the $Mg^{2+}$ content was higher than $Ca^{2+}$, which is common in estuarine environments, and may be attributed to pedogenetic processes, such as soluble salt addition, mainly by seawater intrusion and fluvial deposition in a drainage region of fertile soils, as the Vertisols in the region.

Most of the pedons had CEC values between 25 (2 Agnj and 3 Agnj of P4) and 111 cmolc $kg^{-1}$ (3Agn of P6). Cation exchange capacity (T) values between 22.47 and 45.36 cmolc kg-1, in mangrove soils of the Iriri River in "Canal da Bertioga" (Santos, São Paulo, Brazil) [66]. These values are high due to a great contribution of organic matter and a predominance of the $Na^+$, $Mg^{2+}$, $Ca^{2+}$, and $K^+$.

Although being located in an environment with high deposition of organic and mineral compounds, the studied pedons showed low P availability, with contents from 4.9 (4 Agn of P1) to 7.1 mg $kg^{-1}$ (Agn of P7), compared to the contents in Gleysols (19–35 mg $kg^{-1}$) in "Bertioga Canal" [66]. The Al content in all pedons was close to zero and the acidity in the environment was due to H, as shown by an evaluation of the difference between potential acidity and exchangeable acidity.

Even the pedons under study presenting similar characteristics, pedons formed under riverine influence showed some different characteristics from those observed for pedons formed under marine influence, as follows.

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### 3.4. Pedons formed under riverine influence

The pH levels of pedons under riverine influence (P1–P5), assessed in the field, ranged from moderately acid (pH 6.1–6.5) in the 2A horizon of P1 and P3 to moderately alkaline (pH 7.1–8.1) in the 4A horizon of P2 (**Figure 2**). Studying the mangrove soils under riverine influence in the Marapanim river (Pará, Brazil), Amazon Coast, [21] found pH values similar to those obtained in this study. Just as it was observed for physical characteristics, the shallower pedon (P1) and the deepest pedon (P2) showed chemical characteristics different from the others under riverine influence.

The pH level of P1 increased at a greater depth, showing a value within the alkaline range (8.14), attributed to a higher concentration of $Na^+$, $Mg^{2+}$ and $K^+$ when compared to the others (**Table 4**). The higher pH values of P2 were registered in the deepest horizons, probably as a result of $Mg^{2+}$ accumulation (**Table 4**), something which may have happened because of closeness to rocks or leaching of the element in the higher layers. $Mg^{2+}$ accumulation and the simultaneous increased pH values at a greater depth, in pedons under riverine influence, was not observed only for P4 (**Figure 2**, **Table 3**). The pH value in P3, P4, and P5 ranged from 6.2 to 7.5, and it tended to increase at a greater depth, something which may be explained by $Mg^{2+}$ and $Na^+$ accumulation in the profile (**Figure 2**, **Table 3**).

The Eh values of P1 (328–261 mV) and P2 (337–271 mV) were higher in the surface horizons and layers and they decreased at greater depths. According to [61–68], decreased Eh values at greater depths is usual in estuarine environments. Although this proposition is applicable to all of the pedons assessed, it was observed that, in P3 and P4, the horizons with the highest

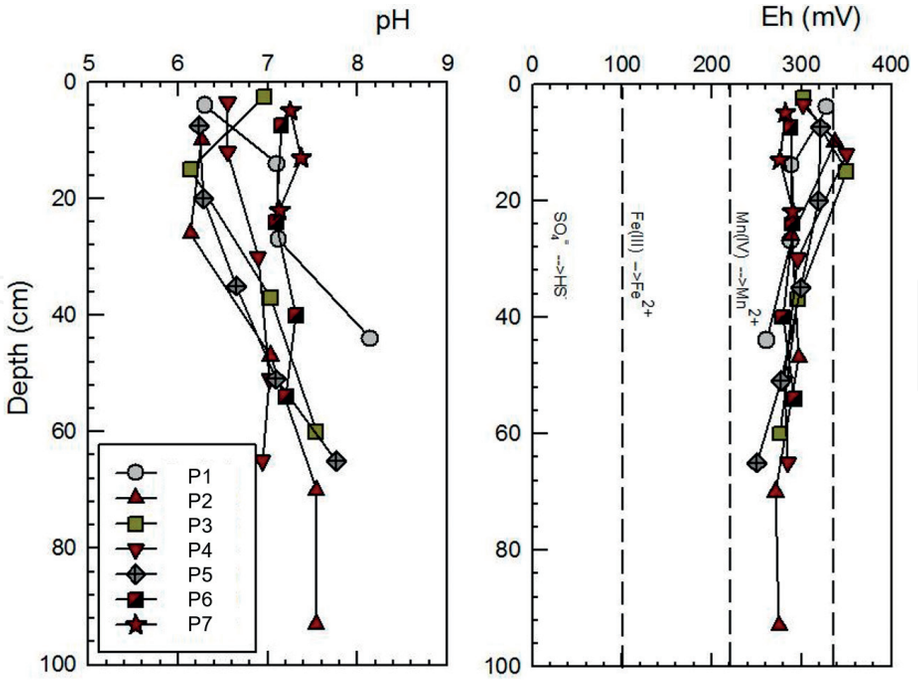



**Figure 2.** Distribution of pH and Eh in depth in the mangrove soil profiles in the Subaé river basin, Santo Amaro, Bahia, Brazil.

Eh values were concentrated in the subsurface layers (**Figure 2**). Water level fluctuation has led the Eh values to range from 66 to 74 mV. The Eh values in this study ranged from oxic (>300 mV) to suboxic (100–300 mV) (**Figure 2**), in the reduction range from $Mn^{4+}$ to $Mn^{2+}$, usually between 200 and 300 mV [69] and they do not reach typical values for anoxic environments (Eh < 100 mV, pH 7), as those obtained by other studies [61, 63, 68, 70]. It was observed by [71] substantial variation in the redox conditions for Rhizophora woods in the Cananeia Lagoon System, Brazil, triggering variation in the redox conditions. The suboxic values in this study may be explained by the collection of samples from the edge of mangroves, sites that, according to [72], favor a quicker drainage and, as a consequence, aeration.

The inverse and significant correlation between pH and Eh ($r = -0.705$, $p < 0.001$, $n = 30$), displayed in **Figure 3**, is mainly due to the presence of Fe oxides. The most common electron acceptors in saturated soils, whose reduction tends to buffer Eh for several weeks and, thanks to the proton consumption, they cause an increase in the pH level [73].

The Crgn horizon observed in P4, which indicates the presence of carbonate material (shells), showed a Ca concentration of 7.8 cmolc $kg^{-1}$ (**Table 4**), but one of the lowest $pH_{H_2O}$ levels (3.6%) (**Table 3**), something which may be attributed to the sulfur concentration (3.7%). Sulfur compounds may contribute to decrease the pH levels in the environment, solubilizing some chemical elements [74].

### 3.5. Pedons formed under marine influence

Pedons under marine influence (P6 and P7) showed pH values around 7.0 along the whole profile (**Figure 2**), something which may be attributed to a higher $Ca^{2+}$ and $Mg^{2+}$ concentration (**Table 4**). Eh values, mainly on the surface of these soils, were lower than those observed for pedons formed under riverine influence. These results confirm the inverse relation between pH and Eh already pointed out.

Eh values of these pedons showed some characteristics different from those observed for the pedons under riverine influence: while the values for pedons under riverine influence

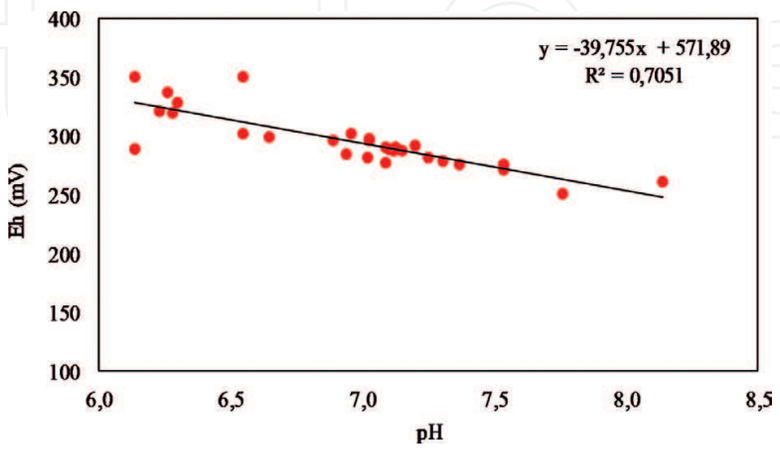



**Figure 3.** Correlation between Eh and pH in the field of the seven pedons from mangrove soils in the Subaé river basin, Santo Amaro, Bahia, Brazil.

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were between 250 and 350 mV, those under marine influence varied: P6 (276–292 mV) and P7 (276–290 mV). These results may be explained by the fact that pedons under marine influence remain submersed for a longer time than those formed under riverine influence. There is no tendency to decrease Eh values at greater depths and the range of Eh values in P6 (13 mV) and P7 (14 mV) is lower than the range for Eh values in the pedons formed under riverine influence.

### 3.6. Heavy metals

Soils may naturally show high concentrations of heavy metals derived from weathering conditions of the source material rich in these elements or due to anthropogenic influence, through the urbanization and industrialization processes. The environment where mangrove soils are formed, such as those assessed in this study with CEC values between 25 and 100 cmolc $kg^{-1}$ (**Table 4**) had a great capacity to retain metals coming from tidal waters, fresh water, rainwater flow, and atmospheric and anthropogenic precipitation. The presence of metals in mangroves is a matter of concern because this environment is the cradle of several animal species used as human food (fish, crab, oyster, etc.).

The Brazilian environmental legislation does not have specific rules for heavy metal concentrations in coastal environments. In this study, in order to assess the normality level of heavy metal concentrations in pedons under riverine (P1–P5) and marine influence (P6 and P7) (**Table 5**), we used Resolution 420/2009, from the Brazilian National Environmental Council [75], which provides for soil quality criteria and values regarding the presence of chemical substances and it classifies the metal contents observed on the soil as preventive values (the threshold concentration of a certain substance on the soil, which is capable of support its main functions) and investigation values (concentration of a certain substance on the soil above the threshold for potential hazards to human health); and the values established by the National Oceanic and Atmospheric Administration [76], which classify the heavy metal content levels on the soil as background, preventive threshold (TEL) and hazard to the biota for marine sediments (PEL).

### 3.7. Pedons formed under riverine influence

Lead is among the heavy metals with a greater effect on the aquatic environment, because it is, at the same time, toxic, persistent, and bioaccumulative within the food chain [77]. Among the pedons under study, P1 had the highest contamination degree, with a Pb concentration at all layers above the prevention threshold established by [75] (**Table 5**). The 4 Abgn horizon of P3 also showed lead concentration levels above the prevention threshold. According to the [76] classification, all layers and horizons of pedons formed under riverine influence showed Pb concentration values between 1 and 3.5 times higher than the TEL value. The 4 Crgnj (P4) layer was an exception, since it showed a Pb concentration level below the background. In contrast, Pb concentration value in the 2 Abgn (P1) layer, 111.3 mg $kg^{-1}$, was very close to the PEL value (112 mg Pb $kg^{-1}$). The Pb concentration levels registered in P1 are a matter of concern, because the pedon is located at an area frequently used by the riparian population to collect shellfish, both for eating and selling.

| Horizon/layer | Pb | Cd | Zn | Mn | Fe |
|---|---|---|---|---|---|
| | mg kg$^{-1}$ | | | | dag kg$^{-1}$ |
| **P1—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | |
| Agn | 85.1 ± 5.7 | 0.9 ± 0.1 | 73.4 ± 1.0 | 128.7 ± 5.0 | 3.6 ± 0.2 |
| 2Abgn | 111.3 ± 2.1 | 1.3 ± 0.1 | 92.4 ± 0.7 | 141.2 ± 2.5 | 5.2 ± 0.0 |
| 3Abgn | 77.9 ± 2.2 | 1.2 ± 0.1 | 95.1 ± 3.5 | 188.4 ± 0.4 | 4.6 ± 0.5 |
| 4Abgn | 82.9 ± 3.1 | 1.2 ± 0.0 | 86.4 ± 1.0 | 235.6 ± 7.5 | 4.5 ± 0.5 |
| **P2—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | |
| Agn | 58.8 ± 1.8 | 0.6 ± 0.0 | 55.2 ± 1.3 | 90.8 ± 2.0 | 1.7 ± 0.3 |
| 2Abgn | 45.9 ± 8.1 | 0.4 ± 0.1 | 54.5 ± 2.2 | 75.7 ± 1.5 | 1.6 ± 0.2 |
| 3Abgn | 70.0 ± 8.0 | 0.8 ± 0.1 | 55.6 ± 4.7 | 77.8 ± 1.2 | 1.9 ± 0.3 |
| 4Abgn | 55.6 ± 5.5 | 4.8 ± 7.2 | 51.4 ± 2.6 | 99.6 ± 3.9 | 2.4 ± 0.6 |
| 5Abgn | 45.0 ± 0.8 | 0.3 ± 0.0 | 50.4 ± 3.9 | 42.8 ± 2.1 | 2.8 ± 0.1 |
| **P3—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | |
| Agn | 36.5 ± 3.4 | 0.7 ± 0.1 | 40.4 ± 0.9 | 82.6 ± 28.6 | 1.6 ± 0.1 |
| 2Abgn | 47.4 ± 2.4 | 0.6 ± 0.1 | 43.3 ± 1.1 | 70.5 ± 1.7 | 2.1 ± 0.0 |
| 3Abgn | 53.6 ± 2.4 | 1.2 ± 0.1 | 57.8 ± 0.9 | 98.8 ± 1.3 | 2.6 ± 0.1 |
| 4Abgn | 72.5 ± 3.8 | 1.5 ± 0.2 | 64.5 ± 1.1 | 138.2 ± 5.4 | 2.9 ± 0.3 |
| **P4—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | |
| Agn | 32.0 ± 5.2 | 0.4 ± 0.2 | 33.7 ± 1.6 | 64.0 ± 2.9 | 1.2 ± 0.1 |
| 2Abgnj | 35.0 ± 1.9 | 0.4 ± 0.1 | 19.5 ± 6.4 | 39.5 ± 0.2 | 0.7 ± 0.3 |
| 3Abgnj | 26.2 ± 2.4 | 0.4 ± 0.0 | 23.3 ± 1.5 | 58.3 ± 1.8 | 1.0 ± 0.1 |
| 4Abgnj | 26.6 ± 4.4 | 0.4 ± 0.0 | 35.3 ± 1.8 | 76.1 ± 2.4 | 1.7 ± 0.0 |
| 4Crgnj | 14.0 ± 3.6 | 0.2 ± 0.0 | 30.9 ± 1.0 | 98.8 ± 3.8 | 1.7 ± 0.1 |
| **P5—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | |
| Agn | 54.4 ± 0.6 | 0.3 ± 0.1 | 73.1 ± 1.4 | 241.9 ± 0.2 | 4.0 ± 0.1 |
| 2Abgn | 65.5 ± 9.8 | 0.9 ± 0.2 | 72.0 ± 3.3 | 120.3 ± 1.1 | 3.5 ± 0.0 |
| 3Abgn | 63.8 ± 7.3 | 1.4 ± 0.0 | 73.9 ± 1.7 | 173.4 ± 2.6 | 4.2 ± 0.0 |
| 4Abgn | 45.3 ± 5.4 | 0.7 ± 0.0 | 48.2 ± 1.2 | 240.1 ± 1.8 | 3.4 ± 0.1 |
| 4Crgn | 49.5 ± 6.9 | 1.0 ± 0.1 | 65.6 ± 0.7 | 205.8 ± 3.1 | 4.6 ± 0.1 |
| **P6—Gleysol thiomorphic orthic (salic) sodic luvissol, potentially toxic, very poorly drained** | | | | | |
| Agn | 43.7 ± 5.8 | 0.6 ± 0.1 | 52.3 ± 1.8 | 141.4 ± 9.1 | 2.8 ± 0.1 |
| 2Abgn | 29.5 ± 1.3 | 0.4 ± 0.0 | 62.4 ± 0.7 | 252.3 ± 4.9 | 4.5 ± 0.4 |
| 3Abgn | 6.2 ± 0.6 | 0.0 ± 0.0 | 62.2 ± 3.9 | 280.4 ± 11.1 | 3.8 ± 0.5 |
| 4Abgn | 14.7 ± 4.6 | 0.0 ± 0.0 | 59.2 ± 0.1 | 268.7 ± 1.0 | 3.9 ± 0.0 |

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| Horizon/layer | Pb | Cd | Zn | Mn | Fe |
|---|---|---|---|---|---|
| | mg kg$^{-1}$ | | | | dag kg$^{-1}$ |
| **P7—Gleysol thiomorphic orthic (salic) sodic luvissol, very poorly drained** | | | | | |
| Agn | 9.0 ± 4.3 | 0.4 ± 0.0 | 68.2 ± 20.2 | 229.3 ± 86.5 | 3.4 ± 0.0 |
| 2Abgn | 11.9 ± 5.0 | 0.2 ± 0.1 | 50.7 ± 2.6 | 271.3 ± 11.0 | 2.7 ± 0.1 |
| 2Crgn | 15.3 ± 0.0 | 0.3 ± 0.1 | 54.8 ± 2.4 | 284.3 ± 7.6 | 2.9 ± 0.1 |
| **CONAMA (2013)** | | | | | |
| Prevention | 72.0 | 1.3 | 300 | — | — |
| **NOAA (1999)** | | | | | |
| Background | 4–17.0 | 0.1–0.3 | 7–38 | 400 | 0.99–1.8 |
| TEL[1] | 30.24 | 0.6 | 124.0 | — | — |
| PEL[2] | 112.0 | 4.2 | 271.0 | — | — |

[1]TEL: It may affect the biological community.

[2]PEL: It causes some effect on the biological community.

**Table 5.** Average and standard deviation of heavy metal concentrations in pedons from the mangrove located in the Subaé river basin, Bahia, Brazil and reference values for metals.

Cadmium is a metal of great mobility within the systems and, therefore, it is hard to establish a distribution characteristic for this metal. Cd values in some horizons of pedons under riverine influence, P1 (2 Abgn), P2 (4 Abgn), P3 (4 Abgn) and P5 (3 Abgn), were equal to or higher than the prevention values established by CONAMA [75]. Cd concentrations in the two pedons under marine influence (P6 and P7) were below the prevention values (**Table 5**). The greater presence of Cd in pedons under riverine influence was also confirmed by the NOAA [76] methodology. Only the 5 Abgn (P2), Crgnj (P4), and Agn (P5) layers showed a Cd concentration equal to or lower than the values accepted for background [76].

The other layers or horizons showed Cd concentration values above the TEL limits and the Abgn layer (P2) showed a Cd concentration level that may cause adverse effects to the biota, i.e. a value above PEL (**Table 5**). The highest Cd concentration levels in pedons under riverine influence may be associated with external waste disposal, such as contamination by waste disposed during lead mining, in the municipality of Santo Amaro, or, according to [78], in urban and industrial activities at the Godavari Estuary, India.

Zn concentration levels in the pedons do not pose a potential risk to the biota, with values below the prevention values established by CONAMA [69] and the TEL values established by the NOAA [76], and the concentration values in all of the P4 layers, the pedon least affected by heavy metals, were lower than the background values (**Table 5**).

As they are significant elements in many source materials, it is difficult to differentiate Mn and Fe concentrations having an anthropogenic origin from the natural ones. Mn concentrations in pedons under riverine influence ranged from 39.5 (2 Abgnj of P4) to 240.1 mg kg$^{-1}$ (4 Abgn of P5), values that are below the background established by [76].

Fe concentrations ranged from 0.7 (2 Abgnj of P4) to 5.2 dag $kg^{-1}$ (2 Abgn of P1). In all pedons under study, either of riverine or marine origin, Fe concentration values were above the background threshold values established by NOAA [76], except for the Agn and 2 Abgn (P2) and Agn (P3) layers and all of the P4 layers, which were below the background concentration (**Table 5**).

### 3.8. Pedons formed under marine influence

Generally, pedons formed under marine influence had heavy metal content levels lower than those in pedons under riverine influence. None of the pedons formed under marine influence showed a Pb concentration value close to the prevention values established by CONAMA [75]. According to NOAA [76], Pb concentrations in the 3 Abgn and 4 Abgn (P6) layers and in the 2 Abgn and Crgn horizons were lower than the background values and only the Agn (P6) layer showed a value higher than the TEL value. Recent study in tropical mangroves showed that mangrove forest act as a biofilter towards heavy metals [79]. Mangrove species compositions change from riverine to marine mangroves due to change in salinity condition and geomorphology. Thus, higher level of species diversity of mangroves is crucial to maintain the health and productivity of coastal ecosystem [79].

Cd concentrations were lower than the threshold value established as background, although in the Agn and 2 Abgn (Pedon 6) and Agn (Pedon 7) layers were higher than the background value (**Table 5**).

Mn concentrations ranged from 141.4 in the Agn horizon of P6 to 284.3 mg $kg^{-1}$ in the 2 Crgn layer of P7, with an increase in the subsurface (**Table 5**). These values were below the background established by NOAA [76]. Mn values in the soils having a marine origin were higher than those obtained in the pedons formed under riverine influence (P2–P4), but similar to P1 and P5 (**Table 5**).

### 3.9. Soil classification

The morphological, physical, and chemical characteristics determined in the seven pedons, regardless of the riverine (P1–P5) or marine (P6 and P7) influence have enabled us to classify the soils, according to the SiBCS [57], as Gleysol thiomorphic orthic (salic) sodic luvissol. If significant areas having pedons similar to those studied herein are mapped, it may be suggested to the SiBCS the Salic nature as the third category level of the theomorphic Gleysols, due to CE values higher than 7 dS $m^{-1}$ at 25°C (**Table 4**).

Based on the characteristics shown, soils were classified according to the Soil Taxonomy [9] as Entisols (Typic Sufalquents), and pedons P5, under riverine influence, and P7, under marine influence, are classified as Haplic Sufalquents, since they show, in some horizon, at a depth between 20 and 50 cm below the surface, less than 80 g $kg^{-1}$ of clay in the fine soil portion, and the others (P1, P2, P3, P4, and P6) are classified as Typic Sufalquents. According to the system World Reference Base (WRB) [71], soils were not classified as Fluvisols Salic Gleyic (Thionic, Sodic), except for pedon P7, which did not show a salic horizon, therefore, it was classified as Fluvisols Gleyic (Thionic, Sodic).

Soils in all of the pedons, either under riverine or marine influence, showed an identical classification, up to the fourth category level regardless irregular characteristics distribution of

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depth, alternation of layers texture and C-org contents, presence of contaminants (heavy metals). It was possible to distinguish only from the fifth category level.

According to Embrapa [57], Gleysols are formed, mainly, due to constant or periodic excessive water, whether they are stratified or not, something which may, many times, lead people to classify these soils as intermediate for Fluvic Neosols. Nevertheless, for the thiomorphic Gleysols there is no definition as intermediate for this class (Fluvic Neosols), at the fourth category level, but, since this is a striking feature of mangrove soils, it was chosen to classify them at the fifth category, in order to suggest the riverine nature, rather than using the texture clustering.

Another characteristic that stands out in soils in the region and has a direct influence on its occupation, use, and management is the presence of heavy metal contaminants, which may occur due to natural factors and processes (source material) or through anthropic processes (introduced into the system by harmful actions). All pedons had heavy metal values higher than those established by the environmental authorities [75, 76], except for P7 (**Table 5**). It is believed that, for this last pedon, the longer distance from the contamination point when compared to the others may have favored its lower concentration.

In the SiBCS, there is no alternative clearly expressed for including heavy metals in the classification, it may be included as a differential characteristic that affects soil use and management for several purposes, also in the fifth category level, based on a chemical attribute that reflects environmental conditions. In the system WRB [59], the prefix Toxic may be used as a formative element for second level units, in some classes, in order to indicate the presence, in any layer within up to 50 cm of the soil surface, of toxic concentrations of organic or inorganic substances that are not the ions Al, Fe, Na, Ca, and Mg.

Based on the classification systems of FAO and the Soil Taxonomy, it was chosen to include the term potentially toxic in the sixth category level, related to the SiBCS, for the soils classes under study having heavy metal concentration above the reference values established by the U.S. National Oceanic and Atmospheric Administration [76]. The pedons under riverine and marine influence were classified as Gleysol thiomorphic orthic (salic) sodic luvissol (potentially toxic, very poorly drained), except for P7, due to the low metal concentration.

## 4. Final remarks

1. Mangrove soils in the Subaé river basin showed different morphological, physical, and chemical characteristics when they were under riverine and marine influence.

2. Mangrove soils in the Subaé river basin showed holomorphic, hydromorphic, and sulfate-reducing conditions, showing some clayeying, as indicated by the morphological, physical, and chemical characteristics.

3. The highest Pb and Cd concentrations were identified in the pedons under riverine influence, probably due to closeness to the Plumbum Mining factory and the lowest concentrations were found in pedon P7, due to greater distance from the factory.

4. All pedons in the soils under study had concentrations of, at least, one heavy metal (Mn, Zn, Pb, Fe, and Cd) above the minimum value warning (TEL), except for pedon P7.

**5.** Mangrove soils, regardless of being under riverine or marine influence, were classified as Gleysol thiomorphic orthic (salic) sodic luvissol (potentially toxic, very poorly drained), due to the low metal concentration.

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