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Soil physicochemical properties and implications for leachate mobility in an Amazonian open dumpsite

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ABSTRACT

Open dumps remain the predominant form of municipal solid waste disposal in many Amazonian municipalities, posing significant risks to soil and water resources due to uncontrolled leachate generation. This study evaluates soil physicochemical properties in an active open dumpsite located in Lábrea, Amazonas State, Brazil, aiming to assess soil quality and infer its potential role in leachate attenuation and contaminant mobility. Eight sampling points were collected at a depth of 0–40 cm and analyzed for pH, organic matter content, and soil texture. The results revealed acidic conditions (pH 4.4–5.8), high organic matter contents (16–39 g kg^{-1}), and a predominance of silt and clay fractions. The fine-textured soil suggests reduced permeability and a potential attenuation capacity for leachate percolation; however, the low pH may enhance the mobility of trace elements and increase environmental vulnerability. The relatively homogeneous spatial distribution of soil properties indicates consistent influence of waste disposal across the site. Although the results suggest some natural attenuation capacity, the combined effects of acidity and continuous waste input highlight the risk of contaminant transport to groundwater. This study provides baseline data for an under-researched Amazonian context and supports the need for integrated monitoring, including contaminant analysis and hydrogeochemical assessment, to guide sustainable waste management strategies.

Keywords: open dumpsite, soil quality, leachate mobility, Amazon region, waste disposal, soil contamination risk.

INTRODUCTION

In Brazil, Federal Law No. 12,305/2010 (Brazil, 2010) establishes the guidelines and standards regulating the proper management of solid waste at the national level, providing for the eradication of open dumps by 2014. This legislation was considered optimistic but innovative, particularly because its legislative process extended over a period of 20 years prior to its enactment. However, after fifteen years of its enforcement, it is observed that few advances have been achieved in the Amazon region. Nonetheless, the federal legislation, State Law No. 4,457/2017 (Amazonas State Government, 2017), instituted the Amazonas State Solid Waste Policy (PERS/AM), emphasizing the need for proper solid waste management and establishing that the State and municipalities, within the scope of their respective responsibilities, must adopt measures to eradicate open dumps.

Solid waste management in the Amazon region is complex and challenging, due both to difficulties in accessing remote areas and to the lack of effective action by public authorities in implementing existing public policies (Melo et al., 2020). According to data from the National Sanitation Information System (SNIS) for the year 2022, there are

1,572 open dumps currently in operation in Brazil. In the state of Amazonas, their distribution is as follows: 46 open dumps, 6 controlled landfills, and only 1 sanitary landfill. In the municipality of Lábrea, Amazonas State, the final disposal of solid waste occurs in an inadequate manner, without treatment or environmentally appropriate destination. According to SNIS (2022) data, the municipality of Lábrea generated approximately 13,620 tonnes of municipal solid waste, which were disposed of improperly on the soil. As highlighted by Alves de Souza-Filho et al. (2019) and Siqueira et al. (2019), water bodies are contaminated by open-air dumps, as these constitute hostile and ecologically unbalanced environments. In the same direction, Aguiar et al. (2021) emphasize that the proper final disposal of municipal solid waste represents one of the greatest challenges in the Amazon, as it poses risks of contamination to water bodies, soil, and human populations.

Despite the well-recognized influence of open dumps on soil degradation and leachate generation (Aguiar et al., 2021), in the Brazilian Amazon there is a scarcity of local, field-based data on basic physical and chemical soil attributes in open disposal areas, which limits environmental diagnoses and mitigation actions (Melo et al., 2020).

This study fills a critical data gap by providing field-based physicochemical characterization of soils from an active open dumpsite in the Brazilian Amazon, where site-specific environmental evidence remains scarce. Unlike studies focused solely on contaminant concentrations, the present work emphasizes how soil texture, acidity, and organic matter jointly influence the potential attenuation and mobility of leachate constituents under tropical conditions. Thus, the objective of this study is to evaluate key physicochemical soil properties (pH, organic matter content, and texture) in an active open dumpsite in the Brazilian Amazon in order to (i) assess soil quality, (ii) infer the potential for leachate attenuation and contaminant mobility, and (iii) provide a baseline environmental diagnosis to support future monitoring and waste management strategies in data-scarce regions.

MATERIALS AND METHODS

Characterization of the study area

The municipality of Lábrea is in the southern mesoregion of the state of Amazonas (Figure 1) (7°15’32” S, 64°47’52” W). This region has a climate classified as tropical monsoon (Am) according to the Köppen–Geiger climate classification. This classification indicates the presence of a season of intense rainfall followed by a more moderate dry season. According to data reported by Franca and Mendonça (2016), the total annual precipitation in the Lábrea area is approximately 2,374 mm, indicating a significant volume of rainfall throughout the year.

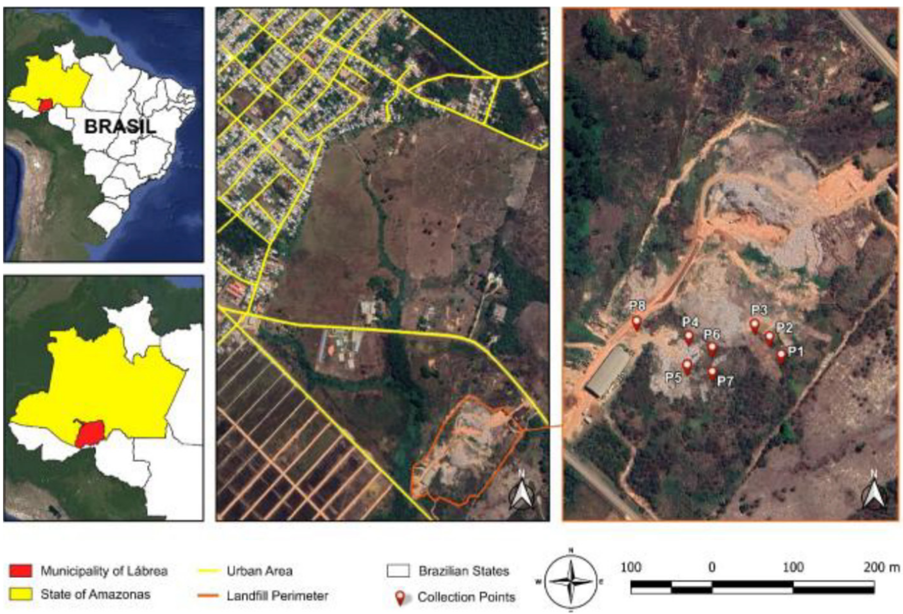

Figure 1. Location map of the study area

Lábrea covers a considerable territorial area, approximately 68,262.680 km². The municipality has a population of 45,448 inhabitants, as recorded by the Brazilian Institute of Geography and Statistics (IBGE) in 2022 (IBGE, 2022). The Lábrea open dump is located outside the urban area of the municipality, near the BR-230 highway. In adjacent areas, on sloping terrain approximately 10 m from point P8, there is a water body, and the well supplying the local administrative building is situated next to the dump. It is important to note that the practice of waste burning occurs continuously as a means of reducing the volume of solid waste at the site.

Field sampling procedures

The sampling locations were defined in the field, followed by photographic records and georeferencing of the sampling points. A total of eight sampling points were considered, designated as P1, P2, P3, P4, P5, P6, P7, and P8, at a depth of 0–40 cm, as shown in Table 1. The sampling points were collected randomly within the disposal area (old and new cells) to ensure an equitable representation of the different conditions present in the study area.

For soil sample collection, a 1 m long manual auger was used. Each collected sample was identified, labeled, and stored in plastic bags corresponding to the location of the sampling point. Samples were collected at a depth of 40 cm, and to avoid cross-contamination between samples, the equipment was cleaned after each sampling point (Figure 2). To represent the study area, points P1, P2, and P3 were collected in the expansion area of the disposal site, while points P4, P5, P6, P7, and P8 were collected in the oldest cell, totaling the sampled points. The sampling design was planned to capture spatial variability between the older disposal cell and the expansion area of the dumpsite; this sample's number was considered sufficient for a preliminary field diagnosis.

Because the objective of this study was exploratory characterization rather than hypothesis testing, the analysis was based primarily on descriptive statistics. The coefficient of variation (CV) was used to provide a first-order assessment of spatial variability across the sampled points.

Sample preparation and determination of soil variables

In the field, the collected samples were identified, labeled, and individually stored in plastic bags (Figure 3). Under controlled conditions, preserving the soil aggregates, the samples were air-dried in the shade and subsequently manually disaggregated and passed through a 2.00 mm sieve. All laboratory determinations were performed using standardized procedures, and care was taken to minimize cross-contamination and operator variability. Analytical equipment was calibrated prior to use, and the procedures followed established protocols to ensure comparability with other soil-quality studies.

pH

Soil pH represents the concentration of H^+ ions in the soil solution and has a direct influence on nutrient availability, metal mobility, and microbial activity. The procedure consisted of weighing 10 g of air-dried fine earth (ADFE) and placing it in a 100 mL plastic beaker, followed by the addition of 20 mL of distilled water (Figure 3). The sample was stirred with an individual glass rod for approximately 60 s and left to stand

Table 1. Geographic location of the sampling points

Point	Description	Coordinates	
		X	Y
P1	New Cell	S 07°16.434’	W 064°46.811’
P2	New Cell	S 07°16.418’	W 064°46.820’
P3	New Cell	S 07°27.508’	W 064°78.805’
P4	New Cell	S 07°21.433’	W 064°41.405’
P5	New Cell	S 07°16.526’	W 064°46.896’
P6	New Cell	S 07°16.529’	W 064°46.889’
P7	New Cell	S 07°16.527’	W 064°46.787’
P8	New Cell	S 07°16.510’	W 064°46.925’

Figure 2. Sample collection procedure: (A) and (D) sampling activities; (B) and (C) sampling points

for 1 h. After the resting period, each sample was gently stirred again, the electrodes were immersed in the homogenized suspension, and the pH value was recorded.

Organic matter

The procedure consisted of weighing 0.5 g of ground soil and placing it in a 250 mL Erlenmeyer flask, to which 10 mL (pipetted) of potassium dichromate solution was added (Figure 3). A blank containing 10 mL of potassium dichromate solution was included, and the volume of ammonium ferrous sulfate consumed was recorded. The mixture was heated to gentle boiling for 5 minutes. After cooling, 80 mL of distilled water (measured with a graduated cylinder), 2 mL of orthophosphoric acid, and 3 drops of diphenylamine indicator were added. The solution was titrated with 0.1 mol L^{-1} ammonium ferrous sulfate solution until the blue color disappeared and was replaced by a green color, and the volume consumed was recorded. The values of organic carbon and, subsequently, organic matter were obtained using Equations 1 and 2. Organic carbon (OC) was determined using the Walkley–Black method, modified by Yeomans and Bremner (1988). Organic matter content (OM) was calculated by multiplying the organic carbon value by a correction factor of 1.724, according to Embrapa (2011).

$$C\ (\text{g/kg}) = (40 - \textit{volume consumed}) \times f \times 0.6 \quad (1)$$

where: f = 40/ volume of ferrous sulfate in the blank test.

$$OM(\text{g/kg}) = C(\text{g/kg}) \times 1.724 \quad (2)$$

Soil texture

Soil texture influences water retention and the potential percolation of compounds through the soil profile. Granulometric analysis was

Figure 3. Soil samples being processed for the determination of soil texture (A) and (B); (C) samples being processed for organic matter determination; and (D) samples in water for pH determination

performed using the pipette method, employing a 0.1 N NaOH solution as a chemical dispersant and mechanical agitation in a high-speed apparatus for 15 minutes, following the methodology proposed by Embrapa (1997). The clay fraction was separated by sedimentation, sand by sieving, and silt was calculated by difference.

RESULTS AND DISCUSSION

Table 2 presents the values of pH, soil texture, and organic matter in the area under the influence of the open dump in the municipality of Lábrea, Amazonas State. Municipal solid waste is disposed of irregularly, without any segregation or sorting for recycling, reduction, or composting. In addition, the practice of incineration at the site is common and is mainly used to reduce the volume of solid waste. The results indicate that the final disposal area of solid waste is predominantly characterized by a silt-dominated soil, with an average silt content of 473.41 g kg^{-1}. Although the silt fraction contributes to reducing soil permeability when compared to sandy soils, the capacity to retain leachate is more strongly associated with the clay fraction. Therefore, the high contents of silt and clay tend to decrease soil permeability (Cui et al., 2026). This behavior is consistent with the function of low-permeability materials used in engineered landfill liners, where fine-grained soils are designed to limit leachate migration. However, as demonstrated by recent studies on waste-based liner materials (Marchiori et al., 2026) permeability reduction alone is insufficient to ensure environmental protection, as chemical compatibility and long-term leaching behavior must also be considered.

Corroborating these findings, Araújo et al. (2012) emphasize that soil texture is one of the most stable physical attributes of soils and is

Table 2. Mean values obtained for pH, organic matter, and soil texture at a depth of 0–40 cm in the open dump of the municipality of Lábrea, Amazonas State

Sampling points	pH (-)	Areia ($g.kg^{-1}$)	Silt ($g.kg^{-1}$)	Clay ($g.kg^{-1}$)	OM ($g.kg^{-1}$)
1	4,68	199,39	529,14	271,47	33,26
2	4,4	107,32	360,12	532,55	16,34
3	4,8	174,69	476,43	348,87	39,12
4	4,4	189,81	433,13	377,06	39,46
5	5,2	152,81	465,18	382,02	39,46
6	4,5	125,39	388,25	486,36	33,82
7	4,62	183,04	463,81	353,15	33,69
8	5,8	214,79	463,81	113,98	34,95
Mean	4,8	168,41	473,41	358,18	33,76
CV	10%	22%	12%	36%	22%

strictly linked to soil structure and water retention. Similarly, Silva et al. (2020) identify soil texture as one of the main indicators of soil quality. However, although the predominance of silt and clay fractions may reduce soil permeability and contribute to the partial attenuation of leachate, this effect is not sufficient to prevent contaminant transport under conditions of continuous waste deposition and high rainfall.

Overall, soil pH values remained below 5, except for sampling points 5 and 8, which presented slightly higher values. With an average pH of 4.8, the observed values indicate high soil acidity, which may favor the potential leaching of heavy metals. In contrast to the results obtained in this study, Gomes et al. (2021), in a study conducted in an area under the influence of an open dump, reported pH values of 6.3, 6.5, and 6.7 at depths of 0–20 cm, 20–40 cm, and 40–60 cm, respectively. On the other hand, Oliveira et al. (2016), when evaluating soils and waters in areas influenced by the disposal of municipal solid waste in the city of Humaitá, Amazonas State, found pH values like those observed in the present study. Decomposition and mineralization processes lead to the production of organic substances of an acidic nature, thereby reducing soil pH in surface layers. From the perspective of Rabelo et al. (2020), the low pH values observed in this study are common in tropical regions, where high rainfall volumes promote the leaching of alkaline metals from upper soil layers by CO_2-containing waters. Under such conditions, soil acidity generally favors the solubilization and mobilization of heavy metals in the soil solution and, consequently, their loss through leaching. The acidic conditions observed (mean pH 4.8) are particularly relevant, as low pH enhances the solubility and mobility of potentially toxic elements such as Fe, Mn, Zn, and Pb (Alloy, 2013). Therefore, future studies are recommended to include the determination of heavy metals in open dump areas.

Organic matter contents ranged from 16.34 to 39.46 g kg^{-1}. In general, most of the sampled points exhibited values above 33 g kg^{-1}, indicating an environment with a high input of organic material, predominantly associated with the disposal of organic waste. According to SNIS data (2022), the municipality of Lábrea, Amazonas State, generated approximately 13,000 tons of solid waste, which are inadequately disposed of directly on the soil. Among these wastes, the organic fraction stands out due to its significant contribution to increasing soil organic matter content. Milhome et al. (2018), when evaluating soils contaminated by open dumps, reported that organic matter accumulation is associated with the disposal of animal carcasses and food waste, which decompose through the activity of microorganisms naturally present in the soil. In that study, organic matter values ranged from 8 to 60 g kg^{-1}. The elevated organic matter contents observed in this study may enhance the adsorption capacity of the soil for organic and inorganic contaminants. Similar behavior has been reported in soils amended with water treatment sludge, where organic-rich materials contribute to increased sorption capacity and improved soil structure (Neto et al., 2018). However, under certain conditions, dissolved organic matter may also facilitate contaminant transport through complexation processes.

According to Lima et al. (2011), solid waste mass is predominantly composed of organic material rich in nutrients and organic matter; thus, when incorporated into the soil, it tends to improve soil fertility. Conversely, Rezende et al. (2017), when investigating the impact of municipal solid waste on soil pH and organic matter in a watershed located in Aquidauana, Mato Grosso do Sul State, reported pH values of 6.2 and organic matter contents of 4.0 g kg^{-1} in the former municipal dump. Therefore, the high organic matter content observed in this study may play a dual role in contaminant dynamics. Elevated organic matter may enhance sorption of selected contaminants and contribute to temporary retention within the superficial soil layer. At the same time, dissolved organic carbon generated during waste decomposition may form soluble complexes with metals and facilitate their transport, indicating that organic matter can play both protective and mobilizing roles depending on site chemistry (Li et al., 2026).

The CV of the evaluated attributes was classified according to Warrick and Nielsen (1980), considering CV < 12% as low variability, values between 12 and 60% as moderate variability, and CV > 60% as high variability (Table 2). pH and silt content exhibited CV values below 12% and were therefore classified as attributes with low variability. In contrast, sand, clay, and organic matter contents showed moderate variability, with CV values ranging between 22 and 36%. The distribution of the analyzed attributes demonstrated relatively uniform behavior, as indicated by the CV values, suggesting that the variables display more homogeneous datasets within the study area. Nevertheless, the results also indicate a condition of concern, as increased soil acidity may reduce microbial activity and, at the same time, enhance the mobility of trace elements. This increased mobility may favor leaching processes, raising the risk of transport of these elements to groundwater and, consequently, increasing the potential for environmental contamination. Soils with significant fine fractions and reactive mineral components may act as natural filters, promoting the removal of contaminants through adsorption and ion exchange mechanisms. Studies on residual soils have demonstrated that clay minerals and fine particles can effectively remove heavy metals from aqueous solutions, reducing their mobility towards aquifers (Silva et al., 2018). Nevertheless, this attenuation capacity is strongly dependent on physicochemical conditions such as pH, organic matter content, and hydraulic loading.

The predominance of silt and clay suggests a reduced permeability relative to coarser soils, which may contribute to partial attenuation of vertical percolation. However, this effect should be interpreted as a potential buffering capacity rather than a guarantee of hydraulic containment, because field conditions in open dumps may include preferential flow paths and heterogeneous waste layers (Marchiori et al., 2026). This study contributes to United Nations (UN, 2015) sustainable development goal (SDG), namely SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production) by providing local evidence to support improvements in solid waste management systems. Indirectly, it is also related to SDG 6 (Clean Water and Sanitation), given the potential link between open dumps, leachate generation, and the risk of contamination of surface and groundwater resources.

CONCLUSIONS

The soils within the Lábrea open dumpsite are characterized by acidic conditions, high organic matter content, and a predominance of silt and clay fractions. These properties suggest dual behavior: while the fine texture may reduce permeability and provide some degree of natural attenuation of leachate, the low pH increases the potential mobility of trace elements, thereby enhancing environmental vulnerability. The relatively homogeneous spatial distribution of soil properties indicates a consistent influence of waste disposal across the study area. From an environmental perspective, the findings highlight that soil characteristics alone are insufficient to prevent contamination risks under continuous waste input. Due to no direct contaminant measurements being performed, the present findings should be interpreted as a baseline indication of environmental susceptibility rather than a quantitative assessment of pollution risk. The combined presence of acidic pH, high rainfall, and continuous waste disposal suggests a favorable scenario for contaminant mobilization and groundwater vulnerability. Nevertheless, direct evaluation of leachate chemistry, dissolved metals, and groundwater quality will be necessary to quantify the actual risk of contaminant migration.. Future research should incorporate contaminant analyses, hydrogeochemical modeling, and long-term monitoring to better quantify environmental risks and support evidence-based decision-making for sustainable waste management in Amazonian municipalities.

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