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ORIGINAL ARTICLE

Soil properties and environmental risk assessment of soils in the surrounding area of Hulene-B waste dump, Maputo (Mozambique)

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Abstract
Soils in areas surrounding landfills are constantly being enriched by heavy metals contained in the leachates, which can subsequently migrate to groundwater. The present investigation aims to characterize soil properties of 71 soil samples collected in the surroundings of Hulene-B waste dump and to determine the landfill pollution index (Ip). Soils properties studied were texture, pH, electrical conductivity, organic matter, color, and moisture. Results revealed that soils properties in the surroundings of Hulene-B waste dump were significantly altered when compared to local background. Ip index classified these soils with very high pollution, indicating a possible migration of contaminants to subsoil and groundwater, suggesting the need for intervention to mitigate the impact.

Keywords Soils · Waste dump · Soil properties · Environmental risk assessment

Introduction

Solid waste disposal surrounding areas are prone to environmental contamination, especially when not planned or monitored (Morita et al. 2020). Wastes produce leachates, an effluent from biological decomposition and dissolved minerals that can contaminate the environment (soil and water) posing a risk to humans and the environment (Kapelewska et al. 2019; Gonçalves et al. 2019). Soil is the first environmental component affected by leachate flows around waste disposal sites (Rapti-Caputo et al. 2006). Huang et al. (2020) suggested that soil is an important receptor for pollutants generated from human activities, acting as a sink for metals. O'Riordan et al. (2021) revealed that soils act as contaminants filter and can control the transport of chemical elements, and other substances, to the hydrosphere, atmosphere and biota.

In urban areas of developing countries, soil and water contamination are often associated with poor solid waste disposal mechanisms (Chu et al. 2020; Parvin and Tareq 2021; Helene and Moreira 2021). The rate of soil and water contamination around landfills is controlled by factors such as landfill age, relevant for leachate production linked to climatic conditions, lithology, and waste disposal conditions (Hussein et al. 2021; Wijekoon et al. 2022). Tropical soils, where oxides (Fe, Al, and Mn) and kaolinitic minerals prevail, have a potential for metal ion uptake contained in leachates (Saentho et al. 2022).

Soils have specific properties, indicative of contamination (Khomiakov 2020; Zamulina et al. 2021). These properties represent a major role in the fixation, adsorption, and absorption of heavy metals (Feng et al. 2021; Yap et al. 2022). Factors such as pH, organic matter (OM), moisture, color, texture, and electrical conductivity (EC), are pointed as relevant to assess contamination processes (Fatoba et al. 2021; Hussein et al. 2021). Soil pH has a major influence on heavy metal solubility (Sparling 2020). Slight to strong alkaline soil pH around dumps have been reported to favor potentially toxic elements (PTEs; e.g., Cr, Mo) dissolution and mobility (Awa and Hadibarata 2020; Zhang and Reardon 2003).

Soil texture also represents an important role in migration and retention of heavy metals (Kosheleva et al. 2018).

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In general, sandy soils are propitious to leachates migration in depth, promoting subsoil and groundwater contamination (Victor et al. 2019; Makuleke et al. 2020). Soil OM influences mobility and speciation of heavy metals, where complexation reactions modify their accumulation potential (Kennou et al. 2015). Soils with low OM content in areas with contamination sources such as Pb, Cu, Hg, and Zn are indicative of possible leaching and migration at depth (Zhang and Reardon 2003).

One of the parameters affecting soil color is OM content (USDA 2001). In solid waste contaminated areas, soil color is influenced by leachates, which are a potential for metal-organic interactions through organic ligands (Lee et al. 2022). Soil color has been used to indicate the possible interference of leachates in soils properties (Gonçalves et al. 2019). Darker colors can be associated with soils affected by leachates (Naveen et al. 2017) and whitish colors are often indicative of leaching processes (Lee et al. 2022). Regarding soil moisture, Salam et al. (2019) studied its effect on the bioavailability of Cu and Pb in contaminated soils and observed that lowest bioavailability of Pb and Cu occurred with higher soil moisture content.

Soil electrical conductivity (EC) is a measure of soil ability to conduct an electric current, being influenced by, e.g., moisture, OM, texture, and others (Grisso et al. 2009). In general, sandy soils present EC ≤ 100 µS/cm (Lund 2008; USDA 2014). In areas surrounding waste dumps, high EC is associated to the enrichment of soils by contaminants, mainly leachates, responsible for the addition of metal ions to soils (Gonçalves et al. 2019; Andaloussi et al. 2021).

Tenodi et al. (2020) and Mama et al. (2021) proposed the study of soil properties to assess the adsorption, absorption, and migration processes of metals associated with leachate migration. Previous studies by Vicente et al. (2006) and Serra (2012) in Maputo city (Mozambique) suggested that inadequate disposal of urban solid wastes is one of the main causes of soil contamination. Hulene-B waste dump is the largest open-air dump in Maputo. Bernardo et al. (2022a) studies showed that Hulene-B surrounding soil and subsoil presented electrical resistivity variations, establishing a link to leachate plumes contamination, with origin in the waste dump. The present study aims to characterize soils properties in the surrounding of Hulene-B waste dump, and to assess pollution risk index.

Materials and methods

Study area

Hulene B waste dump is located in the northern area of Maputo city (Mozambique) (Fig. 1). The dump occupies an area of ~ 17 hm^2 (Serra, 2012), being surrounded by dwellings, with over 75,000 inhabitants (INE 2020). Initially, is was an open quarry, with an estimated variable depth ranging 6–15 m, that was abandoned in 1973 when waste started to be deposited (Ferrão 2006; Palalane and Segala 2008). The dump receives all type of wastes produced in Maputo, e.g., industrial, domestic, commercial, hospital, estimated at > 1000 t/daily (Sarmento et al. 2015; Serra 2012). In the

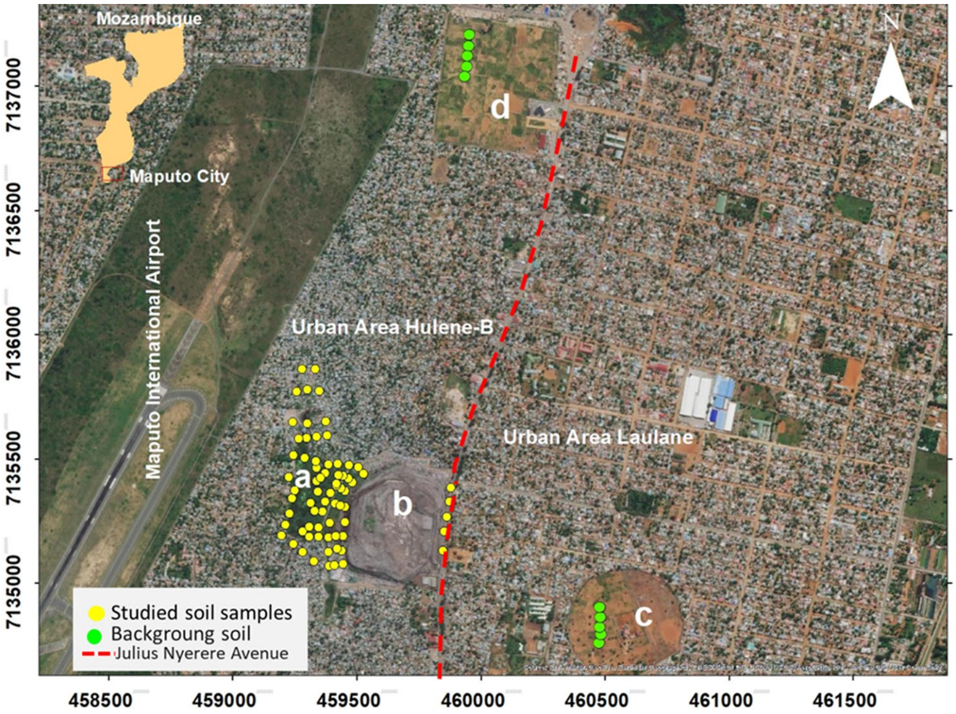

Fig. 1 Studied area context with location of **a** dune depression, **b** Hulene-B waste dump, (**c**, **d**) not-impacted areas

last 10 years, waste has been submitted to bulldozer compaction and a leachate drainage system on southern, northern, and western limits of the dump was added. However, due to its relatively poor structure, leachates are dispersed to the western area, particularly during rainy season.

Geologically, the area belongs to Mesocenozoic sedimentary basin of southern Mozambique, in contact with two lithologies, the Ponta Vermelha (TPv) and the Malhazine (QMa) formations (Afonso 1978; Momade et al. 1996). Topography is of dune type and the dump is located on a slight slope with E–W orientation (Momade et al. 1996). The soils are heterogeneous, comprising materials of the upper Pleistocene QMa and upper Pleistocene to lower Pleistocene TPv formations (Momade et al. 1996). QMa formation consists of coarse to fine, poorly consolidated sands with whitish to reddish colors, fixed by vegetation and by successive consolidation processes while, TPv comprises ferruginous sandstone and red silty sands, which gradually become underneath to yellow and whitish sands (Momade et al. 1996).

Predominant climate is of subtropical type, with mean annual precipitation of ~ 789 mm, with two climatic seasons: (a) hot (mean 25 °C) and rainy period from December to March, representing > 60% of annual precipitation, with its peak in January (~ 125 mm); and (b) dry and cold season, from April to September, with lower temperatures in June and July (mean 21 °C), and scarce precipitation, with minimum values in August (~ 12 mm) (CIAT, 2017). The prevailing winds are SE (Muchangos 1999).

Sampling

A total of 71 soil samples were collected in the surrounding area of Hulene-B dump, in January 2020 (Fig. 1). To determine background, 10 samples were collected in areas considered not impacted by the dump. Soil samples were collected at 0–20 cm depth. Samples were georeferenced and preserved in plastic bags until laboratorial treatment. On the laboratory, samples were oven dried ~ 40 °C (Maputo Pedagogical University, Mozambique). Afterwards, samples were transported to GeoBioTec Research Center Laboratories (University of Aveiro (UAVR), Portugal), for analyses.

Laboratorial analyses

Soil samples were sieved to achieve the < 2000 (sand) and < 63 (silt) µm fractions. pH was determined in the two fractions with a 1:2.5 soil/water solution using a pH meter. Electrical conductivity (EC) was measured under the same conditions as pH in the two fractions, using a high-resolution conductivity meter. Organic matter (OM) content was determined with method proposed by USDA (2001). Moisture was measured based on the procedures defined by Reeuwijk (2002). Soils color was determined using Munsell (2009) soil chart. Silt fraction granulometric distribution was determined with a Micromeritics Sedigraph III Plus grain size analyzer (UAVR). This technique determines the relative mass distribution of a sample by particle size and is based on two physical principles: sedimentation theory (Stokes' law) and the absorption of X-radiation (Beer–Lambert law). The analytical accuracy and precision of the methods were determined using analyses of reference materials and duplicate samples in each analytical set. Results were within 95% confidence limits of the recommended values for the certified material. The relative standard deviation was between 5 and 10%.

pH classes were defined in accordance with USDA (1998): 6.6–7.3 neutral, 7.4–7.8 slightly alkaline, and 7.9–8.4 moderately alkaline. Organic matter classes were defined in accordance with USDA (2001): > 4% high content, 2–4% medium content, and < 2% low content. Electrical conductivity classes were defined based on internationally adopted reference values for sandy soils (Lund, 2008; USDA, 2011): ≤ 100 µS/cm natural medium conductivity, 101–200 µS/cm high conductivity, and > 201 µS/cm very high conductivity. Soil color classes were defined taking in consideration color intensity: blackish, grayish, and brownish. Moisture classes were defined according to the average of the local background value considered standard, 0.41–0.82% high and 0.82–1.9% very high.

Statistical analysis

Descriptive statistics, principal component analysis (PCA) and Spearman correlation were performed using SPSS® v.25 software (IBM, USA). PCA is a data dimensionality reduction technique that aims to explain most of data variation with a small number of independent variables called "principal components" (Škrbić and Đurišić-Mladenović 2010; Hou et al. 2017). Promax rotation was performed which allowed the variance of analyzed parameters to be correlated with each other. Spearman's correlation was used to assess the strength of pairwise correlation of the analyzed soil properties.

Risk assessment

The landfill pollution risk index (I_p) was proposed by Mancini et al. (1999), is based on the determination of vulnerability to aquifer pollution and hazard induced by the quantified landfill as a specific parameter that allows (i) to identify suitable sites to host new waste digestion sites, and (ii) to define the priorities in the control and remediation operations to be fulfilled in case of potential hazard landfills or sites that have already been compromised (Rapti-Caputo et al. 2006). The integration of Ip assessment has been used in many studies to evaluate the risk of groundwater contamination and understanding the properties of the soils where a landfill is located and its surroundings has been highlighted as relevant once soil is considered a superficial defense of the hydrogeological system, where several important processes take place within the soil that make up the attenuation capacity (Civita and Maio 2004).

The method applies eighth variables to assess risk index: (a) volume of deposited waste; (b) leachate drainage; (b) type of waste; (d) waste physical condition; (e) waste biodegradability; (f) monitoring system; (g) waste compaction; and (h) final coating (Chaudhary et al. 2021; Liu et al. 2019; Nadiri et al. 2017). Risk factor (Ri) and risk weight parameter (Wi) for each of the eight variables are described in Table 1. Landfill risk index was determined using $Ip = \sum_{i=1}^{n} \mathrm{W}ixRi$ (Rapti-Caputo et al. 2006; Liu et al. 2019), where I_p corresponds pollution risk index; Wi is weight of the risk parameter (1–5), and Ri the risk factor. Thus, Ip index < 3 represents low pollution potential; Ip 3–7 suggest risk and medium vulnerability; I_p 7–9 indicate risk and high vulnerability, and $I_p > 10$, high contamination risk and immediate intervention measures should be taken to mitigate the impact on groundwater (Rapti-Caputo et al. 2006; Liu et al. 2019).

Results and discussion

Studied soil and background samples were classified as sand (Fig. 2). Sand fraction ranged 90.52–99.32% in studied samples, and 92.84–94.20% in background samples (Table 2).

Table 1 Landfill risk index assessment (Rapti-Caputo et al. 2006)

Variables	Weight	Single risk elements	Reduction factor (R)
Volume of waste deposited	5	< 10 t/day	1
		10 a 50 t/day	0.2
		50 a 500 t/day	0.4
		> 500 t/day	1
Leachate drainage system	5	External and internal drainage	0.1
		Internal drainage	0.3
		Reuse of leachate in the system	0.5
		Absent drainage	1
Type of waste	3	Inert	0.1
		Urban	0.5
		Industrial—non-hazardous	0.8
		Dangerous	1
Physical state of waste	3	Solidified with inert matrix	0.1
		Solid	0.2
		Mud with humidity < 70%	0.5
Stabilization typology	2	Mud with humidity > 70%	1
		Non-biodegradable	0.1
		Aerobic	0.3
		Aerobic and anaerobic	0.5
		Anaerobic	1
Monitoring system	2	Well and geomembrane monitoring	0.1
		Geomembrane	0.3
		Monitoring well	0.5
		Absent	1
Compacting the waste	1	Compacted with pneumatic equipment	0.1
		Compacted with bulldozer	0.2
		Manually compacted	0.5
		No compaction	1
Final coating	1	Compacted soil with clay	0.1
		Compacted clay	0.2
		Non-compacted soil	0.5
		Absent	1

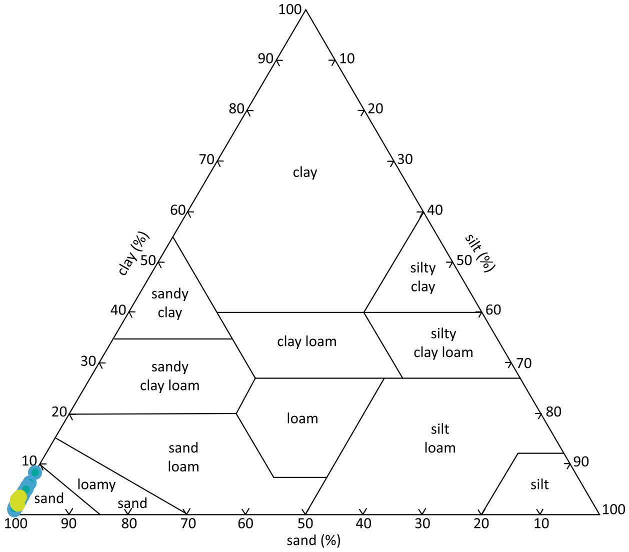

Fig. 2 Soil texture classification of studied soils (blue) and background (yellow) samples

An One-way Anova analysis showed significant differences between studied soils and background samples in sand and clay fraction ($p = 0.000$). The spatial distribution of sand, silt and clay fractions is presented in Fig. 3, being the scale divided in classes of 20% of each fraction range. Samples with higher percentage of coarser particles are distributed in the center of the studied area, corresponding to remobilized soils for construction purposes. Lower sand percentages were found in samples collected in the dump limits. Dakheel et al. (2022) suggested that areas with nearby contamination sources, sandy soils are more vulnerable to leaching and vertical migration of heavy metals to groundwater. Silt fraction, ranged 0.44–7.69%, presented higher contents in samples collected near the dump (Fig. 3). Clay and silt fractions presented similar patterns, with higher clay contents in samples on the dump proximity. This tendency can be associated to leaching due to topographic context, with E–W leachates circulation (Bernardo et al. 2022a, b, c).

Soil pH applies to the concentration of ions (H^+) present in the soil solution, being strongly attracted to negative charges and have capability to replace other cations (Altaf et al. 2021; Soubra et al. 2021). This parameter control soil adsorption and distribution of heavy metals (Naveed et al. 2020). Sparling (2020) suggested that soil pH has a major influence on heavy metals solubility. The pH of the studied 71 soil samples sand fraction ranged 6.7–8.01, with a mean of 7.4; and in silt fraction varied between 7.0 and 8.4, with mean 7.8 (Fig. 4). Spatially, soils pH in the two fractions, were classified as moderately alkaline (7.9–8.4) to slightly alkaline (7.4–7.8). Moderately alkaline class were found in sand fraction samples towards the west of the dump while silt fraction, in samples in the immediate edge of the dump. Neutral pH (6.6–7.3), in silt fraction, was found in samples across the western strip of the dump, while in sand fraction in the northwest direction of the dump. Background samples presented acid pH, ranging 4.2–6.3, and mean 5.25 in sand fraction, and in 5.7–6.3, in silt fraction. Studies suggested that heavy metals mobility tends to be lower with increasing pH, except for metal(loid)s As, Mo and Se (Zimik et al. 2021). Alkaline pH decreases Cu, Co, Fe, Mn, and Zn bioavailability, because of low solubility in this pH range, while Mo, Se, V, As and Cr are more available (Alexakis 2021). In soils with $pH > 6$, occurs the dissociation of H^+ from OH groups in organic matter and Fe and Al oxides, increasing metal adsorption and subsequent precipitation, reducing their bioavailability (Chen et al. 2022; Choppala et al. 2018). Odom et al. (2021) found high levels of Zn in soils around Dompoase landfill in Ghana, under alkaline pH conditions (8.1) and associated it with strong soil enrichment by leachates. El Fadili et al. (2022) reported that soils in the surroundings of Benguerir landfill presented high levels of contamination by Zn and Cu and associated the process of adsorption of these metals with alkaline pH. In tropical soils, such as those in the surroundings of the Hulene-B dump, heavy metal retention can occur under high pH conditions (Campos 2010), due to the predominance of oxidic (Al, Fe and Mn) and kaolinitic mineralogy in the clay fraction, which increases the metal adsorption capacity (Alleoni et al. 2005).

Soil samples EC ranged 43.1–725 µS/cm in sand fraction and 37.5–217 µS/cm in silt fraction (Fig. 5). All samples showed higher EC values when compared to average background samples, of 17.7 µS/cm for sand fraction, and 13.9 µS/cm for silt fraction. Sand fraction, with minimum EC 43.1 µS/cm was found on the northwest area and maximum of 725 µS/cm in the immediate dump boundary to the northwest of the dump. Spatially, the lowest values

Table 2 Granulometric statistical information (in %)

Fraction	Studied soils ($n = 71$)			Background ($n = 10$)		
	Min	Max	Mean ± SD	Min	Max	Mean
Sand	90.52	99.32	97.03 ± 1.89	92.84	95.36	94.20 ± 0.78
Silt	0.44	7.69	2.112 ± 1.41	2.27	3.36	2.74 ± 0.34
Clay	0.22	2.60	0.85 ± 0.52	2.31	3.80	3.06 ± 0.45

SD standard deviation

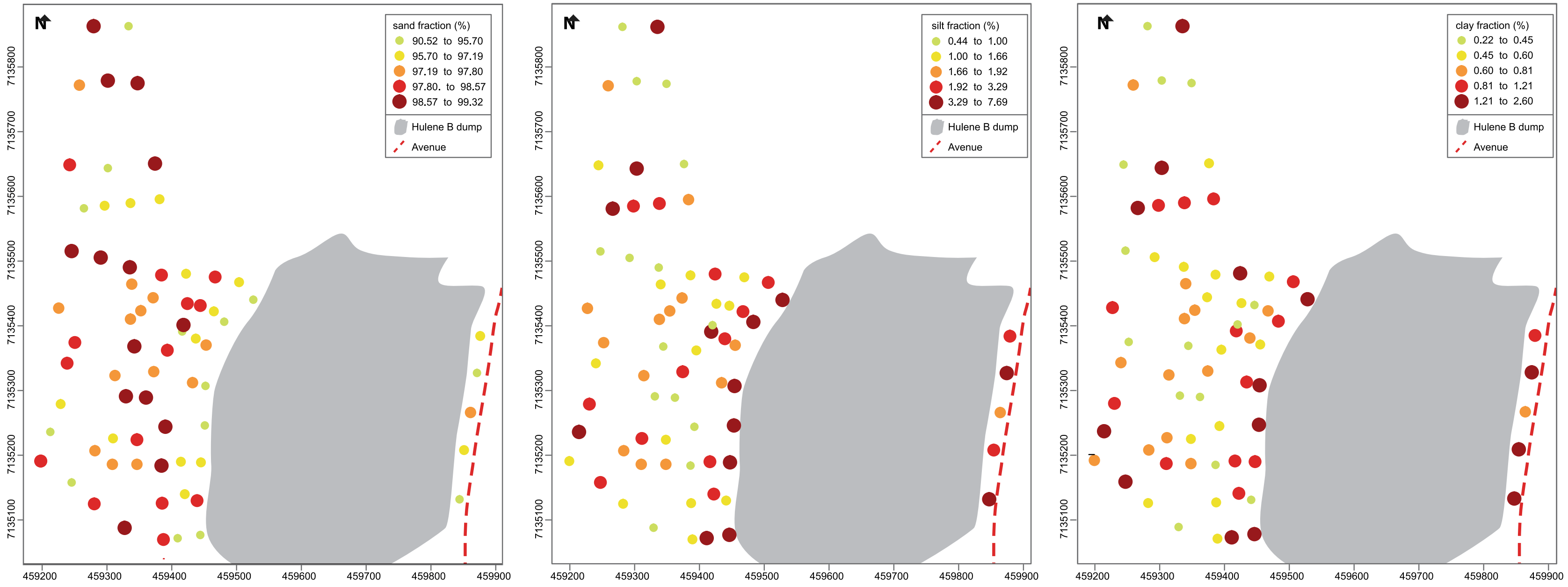

Fig. 3 Granulometric spatial distribution of sand, silt and clay fractions of the studied soils (in %; $n=71$)

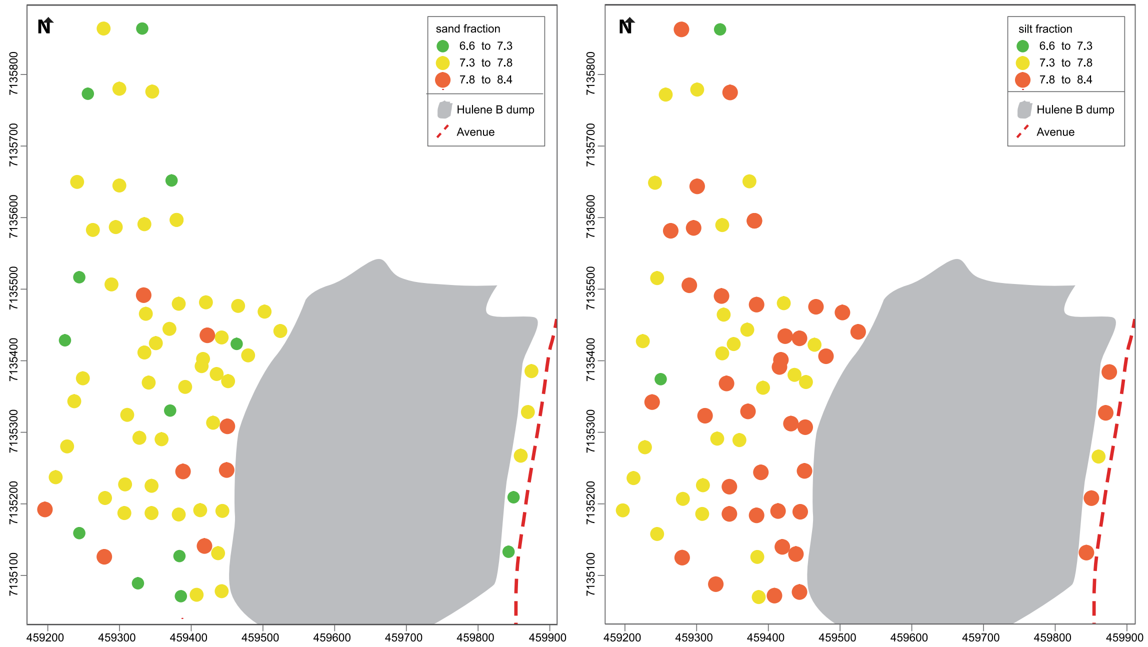

Fig. 4 Soil samples pH in sand and silt fractions

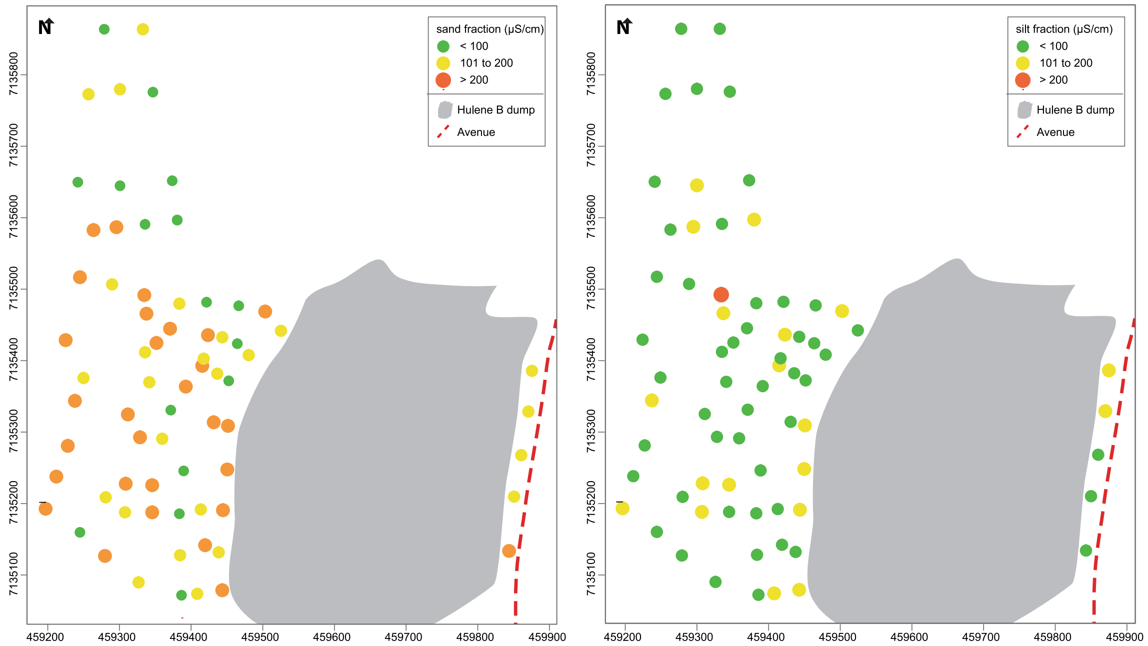

Fig. 5 Soil samples EC in sand and silt fractions

(43.1–100 µS/cm) were randomly distributed, in the center and north of the sampling area and well evidenced in a strip parallel to the dump, corresponding to a disturbed area during construction of the leachate drainage channel. EC ranging 101–200 µS/cm, were found in samples collected near the dump, mainly at the eastern end of the dump towards the center and north of the main sampling area. Higher EC (201–725 µS/cm) were found in samples on the immediate western boundary and with some dispersion to the southwest, west and in the northern direction of the sampling area. Silty fraction, revealed minimum EC 37.5 µS/cm in samples at the northern boundary, corresponding to a transition area between dump upper and lower parts (characterized by intense leaching) and can also be associated with the heavy rainfall of the sampling campaign, promoting the dissolution of salts in the soil and consequently a decrease in soil EC (USDA 2011; Chaaou et al. 2022). Maximum EC 217 µS/cm was found in the northern direction of the sampling center. Spatially lower EC (37.5–100 µS/cm) was predominant throughout the sampling area, followed by EC varying 101–200 µS/cm, predominant at the immediate western boundary and sporadically on the south and north of the sampling area. In both fractions, samples collected on the immediate western boundary exhibited higher EC, suggesting an impact of waste discharges on surrounding soils. The eastern boundary of Hulene-B dump was characterized by high conductivity (Bernardo et al. 2022c), areas with shallow phreatic levels, which may be a factor in the capillary rise of salts and water into the topsoil and consequently an EC increase (USDA 2011). Hussein et al. (2021), found that soils with high EC values were associated with high soil contamination, by As, Cd, Pb and Cr in a study of 6 dumpsites in Malaysia. Similar findings by Wu et al. (2021), on a study of waste dumps in China, and Fatoba et al. (2021) on a waste dump in Nigeria, with contamination by metal-ion enriched leachates.

Soil samples OM distribution is presented in Fig. 6. In studied samples, OM content is scarce (mean 1.1%), with few samples with > 2% in soils collected closer to the dump, in the eastern and western sections, and in western area limit (> 2%, maximum of 4.2%). The higher OM content, suggest an enrichment by contaminants resulting from the migration of surface leachate from the dump and/or by the aeolian deposition of ash from waste burning (Nisari et al. 2021). Lower OM content was found in the center of the sampling area, corresponding to a depression, that might increase OM leachate and surface water migration to the east–west direction, especially during rainy season. Samples OM content, in the western end of the sampling, may be related to vegetation.

Soil samples color distribution is presented in Fig. 6. Blackish samples were found predominantly in areas near the landfill site and the northwest. Brown samples were predominant in the immediate eastern, western, and south-western boundaries of the landfill. Greyish samples were more prevalent throughout the western sampling area. Factors such as plants fixation, may contribute to darker colors in some samples distant from the dump. Color has been associated to OM content, which exhibits an affinity for heavy metal uptake (Dregulo and Bobylev 2020; Sparling 2020). The background samples revealed reddish color in the TPv Formation and reddish brown in the QMa Formation samples. Studies reported that the sandy soils may have color changes, resulting from accumulation processes of OM transported by water, which subsequently settle in the interstitial spaces, and may fixate some contaminants (Seidl et al. 2021). Hussein et al. (2021) suggested that ash resulting from burning solid waste that is transported and deposited changes soils color and enriches them with Hg. Color and OM showed a similar trend, being good indicators for locating areas with possible contamination (Dregulo and Bobylev 2020).

Studied soil samples moisture content is presented in Fig. 6. Background samples mean content was 0.4%, ranging 0.2–0.6%. Samples from dump outskirts revealed an average moisture content of 0.4%, ranging 0.0–1.9%. Samples collected in the immediate edge of the dump showed very alternating moisture contents, with a predominance of high and very high values (0.4–1.9%). In the center of sampling area, occurred a prevalence of moisture contents < 0.4%, alternating with higher 0.4–0.8%. One sample in the immediate north-western boundary of the dump, showed the highest concentration of 1.9%, being the lowest concentration of 0.0% in the southern boundary and central sampling area. In general, sandy soils have low water retention capacity (Zeitoun et al. 2021) and in the surroundings of dumps with surface drainage of leachate whose substrate is sandy soils, the process of leaching and migration of leachate in depth predominates (Zhang et al. 2021), being pointed as the cause of subsoil and groundwater contamination in many studies (Stefania et al. 2019; Wu et al. 2021; Przydatek and Kanownik 2021).

Principal component analysis (PCA)

Principal component analysis reduces a set of variables into a smaller one called principal components (PC), attempting to reveal variables correlation structure and interpret parameters that influence soil samples. In this study, PCs were extracted from 71 samples (sand fraction) and 8 variables with Promax rotation. Three principal components were considered, accounting for 73.14% of the total variance. First component (PC1), explained 40.86% of total variance, defined two groups of variables: sand negatively related to silt and clay variables (Fig. 7), with high negative loadings (> 0.95). Second component (PC2) explained 21.61% of total variance, with positive loading composed by OM, EC, and moisture. Third component (PC3), with 13.66% of variance, groups pH and color variables.

The opposition in PC1 between sand and smaller fractions, was justified by the high sand fraction content. PC2 groups OM, EC, and moisture, influenced by incorporation effects of the metallic ions contained in the leachates, as well as deposition of incineration ashes of contaminated waste from the Hulene-B dump. Samples from the immediate limits of Hulene-B dump showed a spatial distribution that expressed the correlation between high EC, OM, and moisture. PC3, suggested heterogeneous alteration conditions associated to the movement and accumulation of leachates that cause heavy metal contamination, and, the

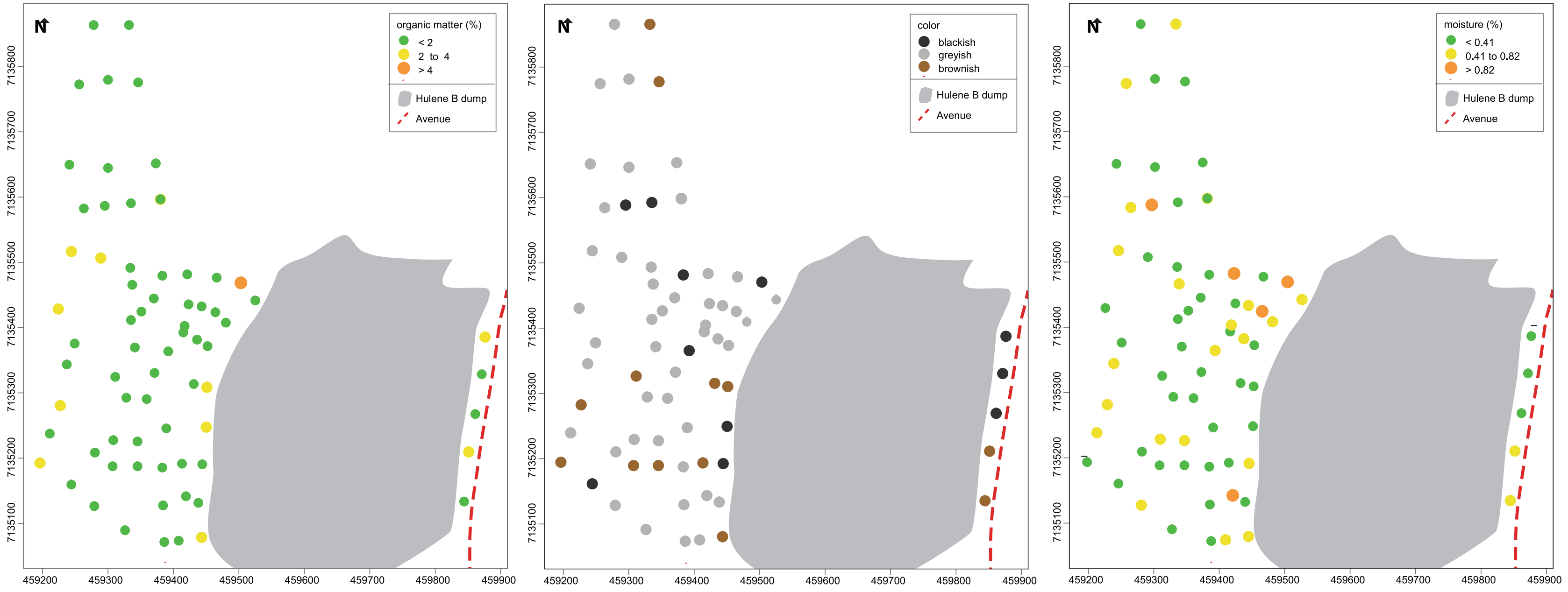

Fig. 6 Soil samples OM content, color, and moisture content

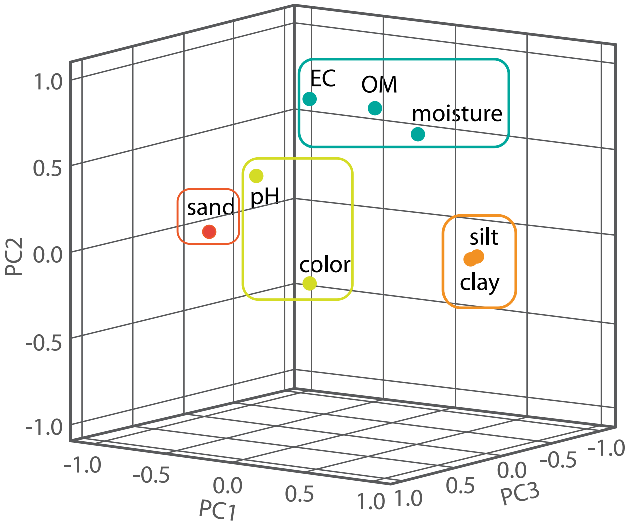

Fig. 7 PCA variables distributed by component

predominance of sandy granulometry that is conducive to vertical leaching of contaminants.

Spearman's correlation (Table 3), in line with PCA showed the same trend. The pairs silt/sand, clay/sand, moisture/sand, pH/clay, color/pH ($p < 0.01$), color/sand, and color/EC ($p < 0.05$) revealed a significant negative correlation. This suggests heterogeneous processes that can be associated with the geo-environmental conditions surrounding the dump, such as predominance of leaching in sandy soils which is intensified by the circulation of leachate-enriched surface water, responsible for significant EC increase and soil color alteration. Pairs clay/silt, EC/OM, pH/sand, pH/EC, moisture/silt, moisture/clay, color/clay ($p < 0.01$) and moisture/OM ($p < 0.05$), revealed a significant positive correlation. The impact of Hulene-B waste dump on soil properties, by incorporation of metal ions from leachate and contaminated ash, alter soil properties in a combined way at the immediate limits of the dump and in a localized manner at various points in the surroundings of the dump.

Landfill risk index assessment (Ip)

The analysis of the geo-environmental and structural context of the dump, allowed to assess risk factor variables weights (Table 4). For the risk factor volume of deposited waste, a maximum score of 1 and corresponding weight is 5 was assigned, taking in consideration a deposition > 1000 t/day (Table 1). For the leachate drainage system, a score of 1 and corresponding weight is 5 was assigned once leachate is dispersed on soil in the surroundings of the dump (Fig. 8). For the type of waste, a value of 0.5 was assigned and a corresponding weight 3. For the stabilization typology was considered 0.3 and a weight of 3, due to dump successive accumulation of waste and a heterogeneous process of waste biodegradation, and continuous accumulation causing a reduction of oxygen in the layers below. The monitoring system was assigned a maximum of 1, with a corresponding value of 2 since there is no monitoring mechanism at the dump. The compaction of the waste is done by bulldozer, so a value of 0.2 was assigned and a corresponding weight of 1. For the final coating, a value of 1 and a corresponding weight of 1 was given since the dump has no coating mechanism.

The factors with the highest scores were the volume of waste deposited (> 1000 t/day) and the conditions of its storage

Table 4 Risk index (Ip) of the studied area

Risk factors	Situation	R	W	R*W
Landfilled waste volume	> 1000 t/day	1	5	5
Drainage system	Drainage absents	1	5	5
Type of waste	Urban	0.5	3	1.5
State of the waste	Solid	0.2	3	0.6
Waste biodegradability	Anaerobic	1	2	2
Site monitoring	Non-existent	1	2	2
Compacting the waste	with bulldozer	0.2	1	0.2
Final coating material	Absent	1	1	1
Ip				17.3

R risk factor, *W* weight parameter, *R*W* risk factor final weight

Table 3 Spearman correlation

	Sand	Silt	Clay	OM	EC	pH	Moisture
Silt	– 0.968**	1					
Clay	– 0.952**	0.868**	1				
OM	– 0.126	0.151	0.135	1			
EC	0.139	– 0.038	– 0.18	0.532**	1		
pH	0.303**	– 0.202	– 0.341**	0.149	0.527**	1	
Moisture	– 0.355**	0.377**	0.349**	0.282*	0.206	– 0.11	1
Color	– 0.279*	0.176	0.348**	– 0.148	– 0.266*	– 0.367**	0.049

**$p < 0.01$

*$p < 0.05$

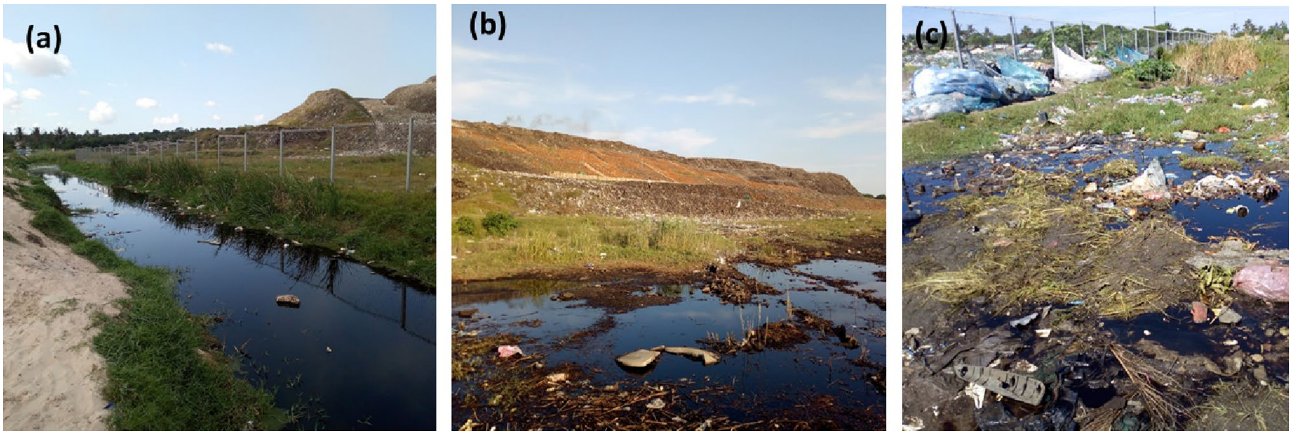

Fig. 8 **a** Leachate drainage channels without isolation, **b** dispersed leachate, **c** uncontrolled leachate flow

(open deposition, no isolation of the leachates from the surrounding environment) and monitoring. These factors were described in many studies as conducive to soil contamination in the surroundings of the dumpsites (Rapti-Caputo et al. 2006; Lothe and Sinha 2017; Liu et al. 2019; Rapti et al. 2021).

Risk factors analysis allowed to classify Ip on the surroundings of the de Hulene-B dump as very high (17.3), an indicator of possible groundwater contamination and need of immediate intervention for impact mitigation (Rapti-Caputo et al. 2006). Structural measures were adopted by local authorities along with the present study sampling campaign, such as the construction of a surface leachate drainage system that could have reduced the risk factor to 2.5 and the overall risk to 14.8. Nevertheless, the constructed system does not systematically control leachate and does not isolate the surrounding environment (soils, groundwater, surface water and cultivated fields in the vicinity of the dump) (Fig. 8).

Soils properties and landfill pollution risk assessment data combination suggested complementarity to understand soil and groundwater contamination risk by leachate. Results showed that soil properties were strongly impacted by the landfill site, as well as spatial areas with greatest changes. The assessment of the landfill pollution risk was relevant, as the factors associated to the management of the landfill site that influence the change of soil properties around the Hulene-B dump were identified. The combination of these results proved to be a knowledge base to be applied in the search for measures to mitigate the impacts of the Hulene-B dump on soil properties and the risk of groundwater contamination.

Conclusion

Soil properties of the samples collected in the surroundings of Hulene-B dump showed a strong alteration when compared to background samples. This suggests a possible contamination and conditions for leachate migration into the subsoil and groundwater. Electrical conductivity showed more significant alterations, with values considered high in all samples around the dump, what can be associated with possible contamination of soils by heavy metals present in leachates and ashes from waste incineration. The predominance of sandy fraction suggested vertical migration of contaminated leachate in depth. Soils pH classified from neutral to slightly alkaline, and a low OM content suggested a higher leaching and migration capacity of contaminants in depth. The landfill pollution index (Ip) was rated very high (16.3) suggesting a possible migration of contaminants to groundwater, a similar result to soil properties. Results highlight the importance of the dump monitoring and the systematic assessment of soil and groundwater contamination levels.

Studies are still needed to understand the temporal dynamics of soils properties once this study sampling took place during rainy season. It is also pertinent to perform chemical and mineralogical analysis of the surrounding soils as well as assess groundwater and biota contamination.

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Data availability Data used is available on the manuscript.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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