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Research article

Sorption–desorption behavior of lateritic soils at low heavy metal concentrations

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ABSTRACT

The increasing solid waste production and leachate-related contamination risks demand effective containment strategies, particularly in tropical regions where lateritic soils are widely considered for landfill liner applications. This study investigates the sorption and desorption behavior of five heavy metals (Cd, Cr, Cu, Mn, and Pb) in lateritic soils derived from quartzite, migmatite, and charnockite parent rocks in southwestern Nigeria. Batch equilibrium experiments were conducted using environmentally relevant metal concentrations (10–100 mg/L) to simulate landfill leachate conditions. Physicochemical characterization revealed acidic to near-neutral pH (4.61–6.73) and a wide range (4.55–14.44 meq/100 g) of cation exchange capacities (CEC), with quartzite derived lateritic soil (QDLS) and migmatite derived lateritic soil (MDLS) exhibiting more favorable geotechnical properties for containment applications despite their lower CEC. Adsorption efficiency increased with initial concentration and varied with parent rock type and metal species, with Cd consistently demonstrating the highest retention (up to 88.8% in MDLS), while Cu exhibited the weakest affinity. The observed selective adsorption sequence observed across all lateritic soils shows the influence of mineralogical composition in enhancing sorption capacity and contaminant attenuation. Sorption data were effectively described by both Freundlich and Langmuir isotherm models ($R^2 \geq 0.70$ in 97% of cases), reflecting the heterogeneous nature of the soils, with Cd exhibiting the highest maximum adsorption capacities of 42.43 mg/g in charnockite derived lateritic soil (CDLS) and 33.38 mg/g in QDLS. Desorption experiments revealed partial reversibility, with hysteresis indices ranging from 1.000 to 1.356, indicating varying risks of metal remobilization. These findings suggest that lateritic soils, particularly those derived from quartzite and migmatite, are viable for landfill liner applications due to their strong metal-binding potential and low desorption tendencies, although their performance may be limited by partial desorption under acidic conditions.

1. Introduction

The increasing volume of municipal solid waste (MSW) worldwide reflects the intertwined pressures of population expansion, urban development, and economic activities, posing a persistent challenge to environmental sustainability [1–3]. This challenge is more pronounced in developing countries, where rapid urbanization and inadequate infrastructure worsen disposal issues [1]. In Nigeria, the problem is particularly acute, with approximately 32 million tons of waste generated annually, about 70% of which is disposed of in landfills (mostly unegineered) due to limited alternative waste management or disposal options [4]. Landfilling remains a dominant waste management strategy worldwide, with 55% of MSW in industrialized nations directed to such facilities [5,6]. However, a critical concern associated with landfilling is the production of leachates laden with toxic heavy metals, which can contaminate soils, aquifers, and surface waters if not adequately contained.

To mitigate these risks, modern landfills incorporate liners designed to restrict leachate migration. These barriers typically include synthetic options like high density polyethylene (HDPE) and natural layers/liners, often composed of compacted clayey materials with low hydraulic conductivity [7,8]. While synthetic liners provide a strong initial shield,

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their vulnerability to damage over time or during deployment elevates the role of natural liners, which offer dual benefits: limiting leachate flow and neutralizing pollutants via sorption and other natural processes [9,10]. Consequently, composite systems combining both liner types are increasingly favored. However, the scarcity of high-quality clayey materials in many regions has driven the exploration of alternative, locally available materials, such as lateritic soils, for use as compacted liners [8, 11,12].

Beyond technical performance, using locally available liner materials also offers clear sustainability benefits. This study supports sustainable engineering by examining the use of locally available lateritic soils as landfill liners, especially in tropical developing regions where rapid urban growth is placing increasing pressure on waste management systems. Using local soils reduces reliance on imported or heavily processed materials, lowers construction costs, and cuts emissions linked to long-distance transport, while encouraging more responsible use of natural resources. These benefits align with several United Nations Sustainable Development Goals. Improved liner performance helps protect groundwater, contributing to SDG 6 (Clean Water and Sanitation). Stronger and more resilient waste containment supports SDG 11 (Sustainable Cities and Communities), while the use of local materials advances SDG 12 (Responsible Consumption and Production). Reduced transport emissions and improved waste containment also support SDG 13 (Climate Action). In addition, by limiting the movement of heavy metals into surrounding soils and ecosystems, the study contributes to SDG 15 (Life on Land), particularly in regions where lateritic soils are widespread.

Residual lateritic soils are extensively distributed across tropical and subtropical regions, including Nigeria, China, and Brazil, and serve as essential geomaterials in various engineering applications such as pavements and earth dams. Their widespread availability, cost-effectiveness, and favorable geotechnical properties have also positioned them as promising materials for landfill liners [13,14]. In particular, their mineralogical composition, predominantly rich in kaolinite and iron oxides, contributes to their potential for contaminant attenuation [15–17]. However, most studies on lateritic soils from Nigeria have focused primarily on their geotechnical suitability as landfill liners, with limited research on their capacity for contaminant retention and attenuation.

Recent studies by [11] and [18] have advanced this understanding by examining the sorption characteristics of lateritic soils derived from various parent rocks in southwestern Nigeria, specifically at elevated heavy metal concentrations (50–500 mg/L). Their findings indicate that sorption capacity varies significantly depending on parent material, with lateritic soils derived from charnockite and granite-gneiss exhibiting superior performance [11]. Furthermore, sorption behavior was found to conform to Langmuir isotherm models, with observed hysteresis indicating partial reversibility in contaminant retention.

Despite these advancements, existing research predominantly investigates heavy metal sorption at relatively high contaminant concentrations (50–200 mg/L), which may not accurately represent the low-level, long-term exposure conditions typical of landfill leachates. The behavior of heavy metals at lower concentrations (10–100 mg/L) remains insufficiently explored, despite its critical importance for environmental risk assessment and long-term containment performance. It is therefore essential to investigate heavy metal behavior at lower concentrations, particularly sorption-desorption dynamics and potential reversibility, given their crucial role in the long-term effectiveness of containment systems. At these lower concentrations, sorption processes may exhibit distinct characteristics, such as linear behavior and reduced competitive effects, which can significantly influence contaminant mobility. To improve containment effectiveness and environmental protection, liner design optimization and predictive model refinement depend on an understanding of these dynamics.

This study addresses this research gap by investigating the sorption and desorption characteristics of lateritic soils from southwestern Nigeria at environmentally relevant heavy metal concentrations (10–100 mg/L). By providing empirical data under realistic field conditions, this research aims to improve the understanding of contaminant attenuation mechanisms in lateritic soils and assess their viability as landfill liners, ultimately contributing to more effective landfill design and long-term environmental protection strategies.

Therefore, this study provides experimentally derived data to support or relevant to the design of lateritic soil liners for experimental protection. We characterized the sorption–desorption behavior at environmentally relevant low concentrations (10–100 mg/L) to generate the distribution coefficients and isotherm parameters for estimating contaminant retardation, hysteresis indices (HI) for evaluating the risk of long-term metal release, and a clear comparative ranking of retention performance among the three lateritic soils derived from different parent rocks. Together, these results offer useful first-level inputs for selecting suitable liner materials, estimating contaminant movement in diffusion-controlled systems, and assessing long-term chemical stability under conservative, acidic leachate conditions.

2. Materials and methods

2.1. Study area and sample collection

This study was conducted in Ekiti State (Iworoko-Ekiti and Ado-Ekiti), Southwestern Nigeria, a region characterized by a tropical climate and diverse geological formations. Ado-Ekiti and Iworoko-Ekiti are underlain by the rocks of the Southwestern Precambrian basement complex [19,20]. Lateritic soil samples were collected from three different sites underlain by quartzite, migmatite, and charnockite parent rocks (Fig. 1). At each location, approximately 5 kg of soil was excavated from the lateritic horizon using a stainless-steel auger. We collected the lateritic soil samples, which had formed over migmatite and charnockite, from an exposed road cut, while those that developed over quartzite were taken from an active borrow pit. The samples were stored in polyethylene bags, air-dried at room temperature ($25 \pm 2^{\circ}C$) for 7 days, and sieved through a 2-mm mesh to remove coarse debris and ensure uniformity. Homogenized subsamples were prepared by pooling and mixing the sieved soils from each site to ensure representativeness.

2.2. Physicochemical characterization

The physicochemical properties of the lateritic soils were assessed to evaluate their suitability as landfill liners. Grain size distribution was determined using mechanical sieving and hydrometer techniques in accordance with [21]. To enhance particle dispersion during sieve analysis, each sample was pre-soaked in a dilute Calgon solution for twenty-four hours with intermittent agitation before undergoing wet sieving. Consistency limits (plastic limit, liquid limit, and plasticity index) were determined following [21] for the soil fraction passing a 425 μm sieve using the Casagrande apparatus and rolling thread method. Before testing, the sieved fractions were mixed with water and left to hydrate for 24 h.

The soil pH was determined in a 1:2.5 soil-to-deionized water suspension using a calibrated pH meter (Hanna HI98130). A representative soil sample, passing through a No. 40 sieve, was placed in a beaker, and 75 mL of demineralized water was added. The mixture was stirred for 2 min and then allowed to stand for one (1) hour with occasional stirring. After the equilibration period, the pH of the suspension was measured using the pH meter. Cation exchange capacity (CEC) was determined using the ammonium acetate method as outlined by [22], involving saturation with 1 M ammonium acetate, displacement with sodium chloride, and quantification of exchanged ammonium via distillation and titration.

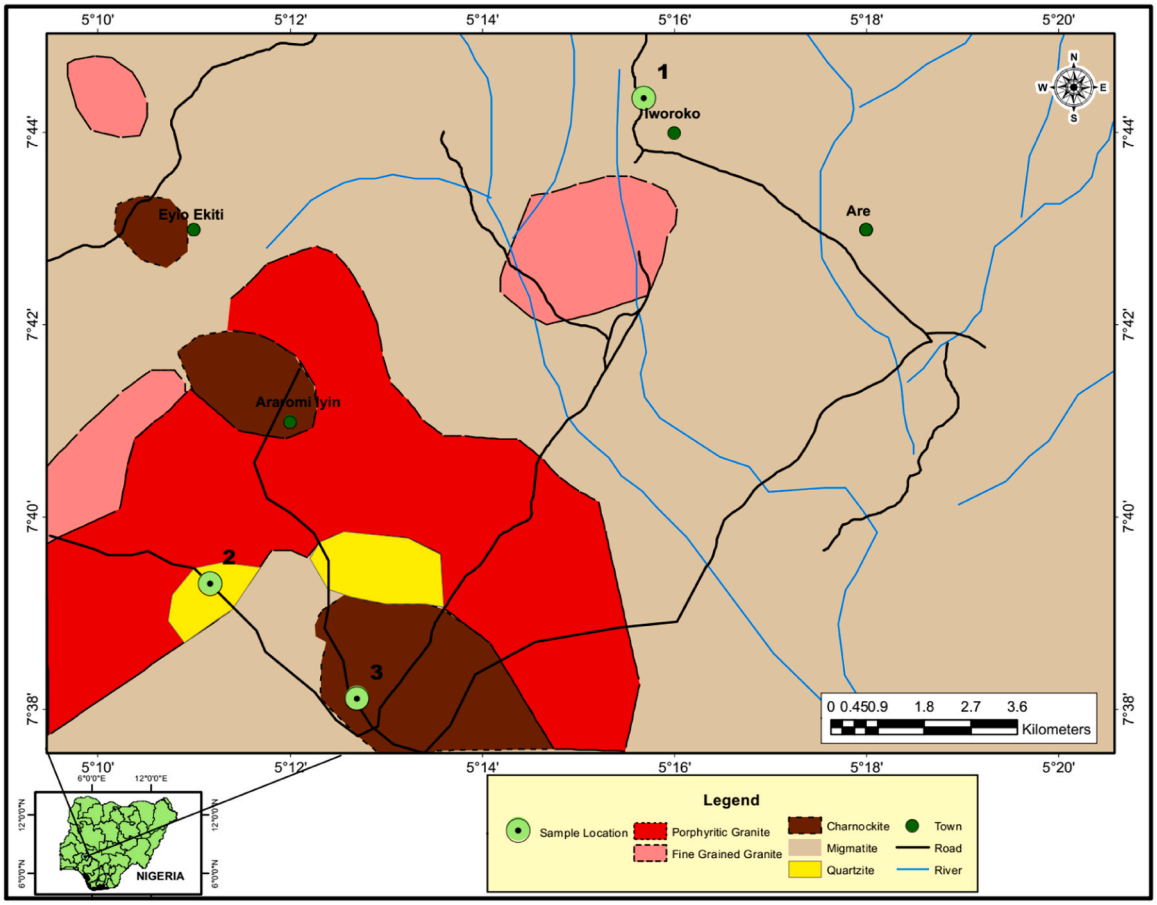


Fig. 1. Geological map of Ado-Ekiti and its environs indicating the sample locations.

2.3. Batch sorption and desorption experiments

Batch equilibrium sorption experiments were performed on the lateritic soil samples following the [23] method to evaluate their capacity to retain heavy metals. Five heavy metals—cadmium (Cd), chromium (Cr), copper (Cu), manganese (Mn), and lead (Pb)—were selected based on their documented presence in leachates and soils around most dumpsite in the study area [1,11,24]. Stock solutions with concentrations of 10, 25, 50, 75, and 100 mg/L were prepared in deionized water using analytical-grade metal nitrates: $Cd(NO_3)_2.4H_2O$, $Cu(NO_3)_2.3H_2O$, $Mn(NO_3)_2.4H_2O$, $Pb(NO_3)_2$ and $Cr(NO_3)_3.9H_2O$. These salts provided cadmium, copper, manganese, lead, and chromium in their dissolved ionic forms (Cd^{2+}, Cu^{2+}, Mn^{2+}, Pb^{2+}, and Cr^{3+}), respectively. Chromium was studied exclusively in its trivalent form (Cr^{3+}); hexavalent chromium (Cr(VI)) species were not used in this study.

All synthetic metal solutions were adjusted to pH 2.5–3.0 using dilute HNO_3. This pH range was chosen to reflect acidic leachate conditions typical of the early acidogenic stage of landfill development, when the buildup of organic acids produces strong acidic pore fluids. In practice, landfill leachate pH can vary widely, often ranging from about 4–9 as a landfill matures. The selected pH therefore represents an intentionally conservative, acidic scenario. It allows assessment of metal mobility and liner performance under worst-case conditions, while also maintaining metal solubility and avoiding precipitation that commonly occurs for many divalent metals at higher pH values (e.g., pH > 6).

For each sorption test, 5 g of homogenized soil (calculated on an oven-dry basis) was placed into a 150 mL Nalgene centrifuge tube, followed by the addition of 100 mL of the respective metal solution, yielding a soil-to-solution ratio of 1:20. Soil masses were corrected for residual moisture by drying representative subsamples at 105 °C to constant weight. The suspensions were agitated on a rotary shaker for 24 h at room temperature (25 ± 2 °C) to attain equilibrium. Preliminary kinetic tests conducted on representative samples confirmed that sorption equilibrium was effectively achieved within 18–24 h, with no significant additional uptake thereafter. This 24 h duration aligns with standard batch sorption protocols for heavy metals in soils [25,26] and prior studies on similar lateritic soils from southwestern Nigeria [11].

After equilibration, the suspensions were separated by centrifugation at approximately 3000 × g (equivalent to 4000 rpm for the centrifuge rotor used) for 15 min, and the supernatant was filtered through a 0.45 μm Whatman filter paper. Residual heavy metal concentrations in the filtrate were determined using atomic absorption spectrometry (AAS; PerkinElmer Analyst 400). The 24 h batch experiments conducted at a high soil-to-liquid ratio (1:20) were designed to evaluate the maximum level of metal retention capacity and reversibility under well-mixed conditions. This approach provides conservative estimates of the attenuation potential of the soils and serves as a first-order screening tool for preliminary assessment of their suitability as liner materials.

Metal concentrations were determined using a PerkinElmer Analyst 400 Atomic Absorption Spectrophotometer (AAS). The instrument was calibrated daily using a five-point standard curve (0.5–5.0 mg/L for each metal) prepared from certified single-element stock solutions (Merck, Germany). Calibration linearity was confirmed with correlation coefficients (R^2) ≥ 0.995. Samples exceeding the calibration range were appropriately diluted prior to analysis.

Calibration accuracy was verified every 10 samples using an independent mid-range standard, with deviations maintained within ±5%. Method blanks (deionized water) and matrix blanks (soil with deionized water) were analyzed with each batch to correct for background and matrix effects. The method detection limit (MDL), calculated as three

times the standard deviation of seven replicate blank measurements, was 0.02 mg/L for Cd, 0.03 mg/L for Cr and Cu, 0.04 mg/L for Mn, and 0.05 mg/L for Pb. Spike recovery tests conducted on selected soil extracts yielded recoveries between 92% and 108%, confirming acceptable analytical accuracy and minimal matrix interference.

The soil residue post-supernatant removal was air-dried and digested with aqua regia (HNO_3:HCl,1:3 v/v), then analyzed via AAS to quantify retained heavy metals. For desorption studies, the soil residue was resuspended in 100 mL of a 0.1 M acetate buffer solution (pH ≈ 4.5–5.0) following [27] to evaluate the reversibility of metal retention under controlled pH conditions. An acetate buffer was chosen as a weak electrolyte to represent mildly acidic leachate conditions. This approach allows controlled metal release while avoiding strong reactions that could dissolve minerals or alter the soil structure. The suspensions were agitated for 24 h, centrifuged at approximately 3000 × g for 15 min, and the supernatants were analyzed by AAS to determine desorbed metal concentrations. The pH of the desorption solutions was measured after equilibration and remained between 4.4 and 5.1, confirming that buffering conditions were stable throughout the desorption process.

All adsorption and desorption experiments were conducted in duplicate (n = 2), and the reported values represent the mean of the two independent measurements. The variability between replicates is reported as standard deviation

2.4. Data Analysis and Calculations

The amount of heavy metal adsorbed per gram of soil at equilibrium (q_{eq}, mg/g) was calculated as:

$$q_{eq} = \frac{C_i - C_e}{m} * V$$

where: C_i = initial heavy metal concentration in the stock solution (mg/L), C_e = equilibrium heavy metal concentration in the supernatant (mg/L), V = volume of the stock solution (L, here 0.1 L), m = mass of the soil sample (g, here 5 g).

The adsorption efficiency (% adsorbed) was computed using:

$$\%\quad absorbed = \frac{C_i - C_e}{C_i} * 100$$

The quantity of heavy metal desorbed by the soils at equilibrium (q_{de}, mg/g) was determined as:

$$q_{de} = \frac{C_d}{m} * V$$

where: C_d = concentration of the heavy metal in the desorption supernatant (mg/L)

Sorption data were fitted to both the Freundlich and Langmuir isotherm models to characterize adsorption behavior. The Freundlich isotherm, suitable for heterogeneous surfaces, is expressed as:

$$q_{eq} = K_F.C_e^{1/n}$$

where: K_F = Freundlich constant ($mg^{(1-1/n)}\ L^{(1/n)}\ g^{(-1)}$), 1/n = adsorption intensity (unitless).

The linearized form, $\log q_{eq} = \log K_F + (1/n).\log C_e$, was used to estimate K_F and 1/n.

The Langmuir isotherm, assuming monolayer adsorption on homogeneous sites, is given by:

$$\frac{1}{q_{eq}} = \frac{1}{q_{max} b} + \frac{1}{c_e}$$

where: q_{max}= maximum adsorption capacity (mg/g), K_L = Langmuir constant (L/mg).

Parameters for both models were calculated via linear regression, with fit quality assessed using the coefficient of determination (R^2). Desorption data were similarly modeled to evaluate reversibility and hysteresis.

3. Results and discussion

3.1. Grain size distribution

Table 1 presents the particle size distribution of the lateritic soils after air-drying at room temperature. The results indicate that grain size distribution is influenced by the parent rock type. As shown in Table 1, the lateritic soils exhibit a well-graded composition, with gravel ranging from 0.5 to 5.3%, sand from 44.7 to 63.1%, silt from 14.0 to 21.2%, and clay from 15.7 to 33.2%. This grading pattern is characteristic of lateritic soils derived from felsic rocks, corroborating findings from previous studies [17,28]. Well-graded soils are typically more compactable, resulting in reduced porosity and permeability, as well as improved workability compared to uniformly graded materials [29].

Based on the modified [30] classification chart (Fig. 2), these lateritic soils are predominantly categorized as sandy fines or sand and fines. This classification reflects the significant presence of clay- and silt-sized particles alongside sand, which is advantageous for soils used in landfill liners. These fine fractions help reduce hydraulic conductivity and possibly improve the liners' ability to prevent leachate migration

Although there is general consensus on acceptable gravel and silt content for liner materials, previous studies [8,13,31] have reported variations in the recommended maximum particle size, clay content, and fines proportion. For example, [32] recommends a maximum particle size of less than 25 mm, while [33] suggests a limit of less than 50 mm. Similarly, clay content recommendations vary as well, with [34] proposing at least 15%, [35] at least 25%, and [36] at least 30%. Recommendations for fines also differ, with thresholds of > 20% [36], > 30% [32], and > 50% [35]. Notably, the lateritic soils studied, regardless of parent rock, did not meet all of these specified criteria for grain size proportions.

According to the matrix classification chart developed by [37] for evaluating the suitability of soils as liners, the grain size distribution indicates that most of the samples fall into categories deemed either "useful" or "unsuitable without treatment" (Fig. 3). This classification (unsuitable without treatment) may be attributed to the relatively high sand content, which suggests a coarser texture, potentially increasing permeability and reducing the soil's capacity to inhibit leachate migration.

None of the soils exceed 50% clay-sized particles, a threshold that could achieve low hydraulic conductivity in laboratory tests but would

Table 1
Fractional percentages obtained for samples of the three lateritic soils.

Lateritic Soil	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Fines (%)
MDLS	2.4	63.1	16.5	18.0	34.5
	3.5	53.6	18.4	24.5	42.9
	5.3	61.4	17.0	16.3	33.3
	3.5	56.5	17.7	22.3	40.0
	3.4	55.5	16.5	24.6	41.1
	4.1	55.1	17.9	22.9	40.8
QDLS	2.8	60.7	20.8	15.7	36.5
	2.5	59.2	14.4	23.9	38.3
	2.8	60.0	14.4	22.8	37.2
	2.6	60.5	14.0	22.9	36.9
	2.3	59.7	17.3	20.7	38.0
	2.6	60.0	19.1	18.3	37.4
CDLS	0.8	46.5	20.5	32.2	52.7
	0.6	45.8	21.0	32.6	53.6
	0.7	46.3	20.1	32.9	53.0
	0.9	44.7	21.2	33.2	54.4
	0.5	46	20.9	32.6	53.5
	0.8	46.8	19.4	33.0	52.4

QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil; MDLS: Migmatite derived lateritic soil.

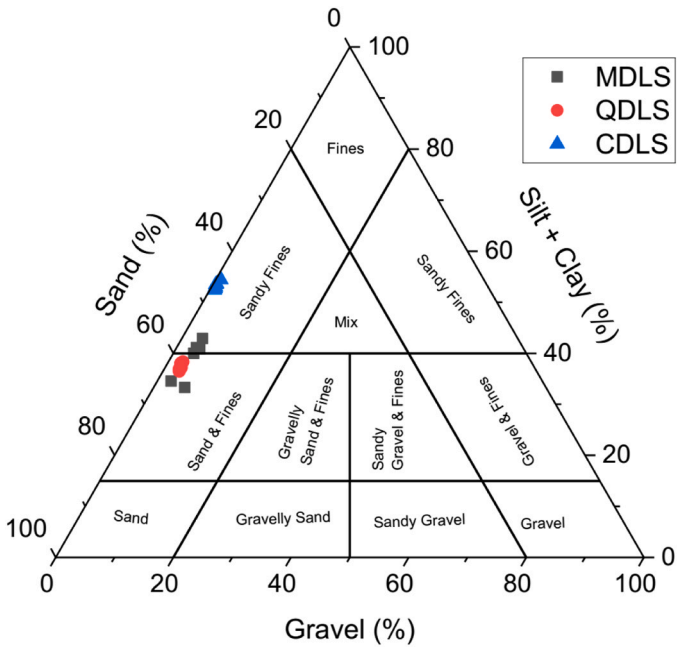


Fig. 2. Classification of the lateritic soils [30]. QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil; MDLS: Migmatite derived lateritic soil.

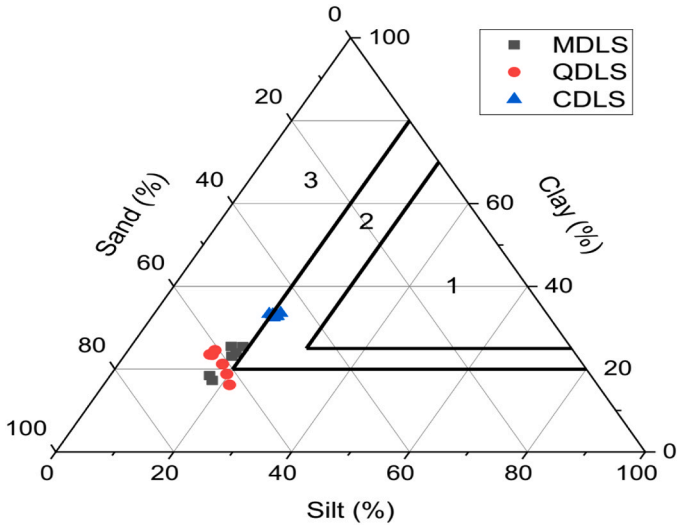


Fig. 3. Sample distribution on the modified Matrix classification chart showing suitability for soil liner applications (adapted from [37]). QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil; MDLS: Migmatite derived lateritic soil; 1: very useful; 2: useful; 3: unsuitable without treatment.

pose challenges for practical field compaction as a liner [38]. Moreover, all samples contain appreciable amounts of sand-sized particles, which help mitigate volumetric shrinkage [39]. In addition, the substantial fines content contributes to increased surface area, further reducing leachate mobility.

3.2. Consistency limits

Table 2 presents the consistency limits of the three lateritic soil samples, while Figs. 4 and 5 present their positions on the Casagrande plasticity chart and their clay activity, respectively. Based on the Casagrande classification, most of the soils plot above the A-line, indicating they are predominantly inorganic clays with low plasticity and

Table 2
Consistency limits of the lateritic soil samples.

Lateritic Soil	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
MDLS	40.6	23.8	16.8
	38.6	21.7	16.9
	41.4	24.1	17.3
	38.5	21.9	16.6
	39.2	21.4	17.8
	43.7	25.8	17.9
QDLS	32.4	18.8	13.6
	33.2	18.4	14.8
	32.8	18.5	14.3
	35.5	19.2	16.3
	34.1	18.9	15.2
	32.7	20.5	12.2
CDLS	42	19.4	22.6
	45	19.7	25.3
	49	19.5	29.5
	55	21.1	33.9
	46	20.5	25.5
	50	23.3	26.7

QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil; MDLS: Migmatite derived lateritic soil

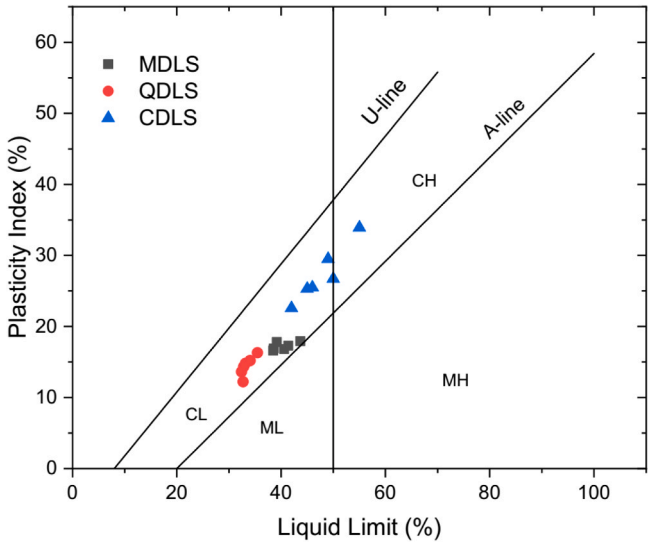


Fig. 4. Casagrande [41] plasticity classification of the lateritic soils. QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil; MDLS: Migmatite derived lateritic soil; CL: Inorganic clays of low plasticity; CH: Inorganic clays of high plasticity; ML: Inorganic silts of low compressibility; MH: Inorganic silts of high compressibility.

compressibility. One exception, a sample derived from charnockite, falls into the category of inorganic clays with high plasticity and compressibility. The suitability of fine-grained soils for use as landfill liners is often evaluated based on their plasticity characteristics, as defined by the Unified Soil Classification System (USCS). Soil plotting above the A-line on the Casagrande Plasticity Chart generally exhibits the low permeability and workability required for effective liners [40].

Among the samples, the lateritic soil samples derived from quartzite have the lowest consistency limits, likely due to their relatively high proportion of coarse particles. The average plasticity index of all soils was below 35%, suggesting minimal shrinkage potential [33]. Furthermore, the liquid limits of the studied soils exceed the minimum threshold of 30% recommended by [34], while remaining well below the upper limit of 90% set by [42]. The plasticity indices also align with the range of 10–30% recommended by [43] for landfill liners, and do not exceed the maximum thresholds suggested by UKEPA [42].

Fig. 5 shows that the activity values of the soils range between 0.3

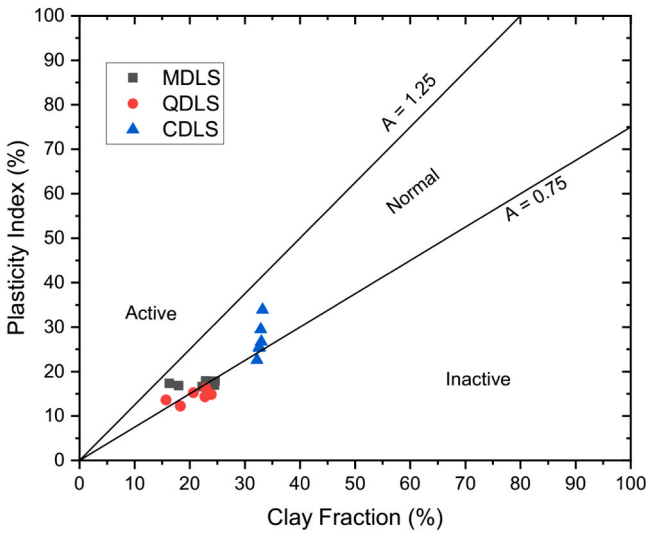


Fig. 5. Activity chart of the lateritic soils derived from the different parent materials. QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil; MDLS: Migmatite derived lateritic soil.

and 1.25, classifying them as inactive to normal, and thus indicating low to moderate swelling potential. This range complies with the values proposed by [36] for landfill liner suitability. Although soils with higher activity may exhibit lower permeability, they are often more susceptible to contaminant transport. The moderate activity values observed in these samples suggest a balance between low permeability and reduced vulnerability to contaminant migration, making them suitable candidates for landfill liner applications.

3.3. pH and CEC

The pH values of the lateritic soils range from 4.61 to 6.73 (Table 3), indicating an acidic environment—a key characteristic of laterization [44]. Such acidity is typical of tropical humid regions, where high rainfall enhances the formation of acidic compounds contributing to soil acidification [45]. These values reflect an acidic to near-neutral weathering regime, consistent with the findings of [46], and [47]. The acidic nature of these soils is primarily the result of intense leaching, which removes base-forming cations such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}, while leaving behind iron and aluminum oxides [25]. These sesquioxides undergo hydrolysis, releasing hydrogen ions that further reduce soil pH. Variations in pH among the samples are influenced by factors such as the extent of laterization, mineralogical composition, degree of leaching, and microbial activity [48].

Table 3
The pH and CEC of the lateritic soil samples.

Lateritic Soil	CEC (meq/100 g)	pH
MDLS	4.55	4.61
	4.85	4.83
	4.96	4.92
	4.67	5.03
	4.90	5.14
	4.89	4.75
QDLS	8.58	5.23
	9.02	5.31
	8.33	5.52
	8.46	5.63
	8.89	5.71
	8.47	5.42
CDLS	14.44	6.23
	14.28	6.34
	13.54	6.51
	13.97	6.62
	14.00	6.73
	13.78	6.39

QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil; MDLS: Migmatite derived lateritic soil

While acidic soils generally have lower heavy metal sorption capacities compared to their alkaline counterparts, they are not necessarily unsuitable for use as landfill liners. According to [49], metal retention improves with increasing pH due to enhanced sorption and inner-sphere complexation. However, research by [50] demonstrates that even under acidic conditions, trace metals can still be effectively retained through sorptive mechanisms. Notably, the average pH values of the studied lateritic soils fall within a range conducive to the adsorption of common heavy metals such as lead and copper [51], supporting their suitability for landfill barrier applications.

Cation Exchange Capacity (CEC) gives an estimate of the total number of cations, expressed in milliequivalents (meq), that are needed to neutralize 100 g of soil [10]. It represents the total exchangeable cations held by the soil's negatively charged surfaces, primarily clay minerals and organic matter [9]. The CEC of the lateritic soils (Table 3) falls within the typical range for kaolinite-dominated soils, approximately 5–20 meq/100 g, reflecting their characteristic low-charge clay mineralogy. This mineralogical composition implies that the soils are relatively stable and less prone to structural changes compared to soils dominated by higher-CEC minerals such as montmorillonite. Higher CEC soils are often more susceptible to variations in double-layer thickness, leading to flocculation or dispersion, which in turn can impact the soil's hydraulic conductivity [52].

Although there is no universally established minimum CEC standard for landfill liners, a threshold of 10 meq/100 g is often referenced in the literature [36]. Some of the CEC values of the tested lateritic soils fall below the suggested minimum, while others are close to or slightly above this suggested minimum. As such, while they may not exhibit exceptionally high exchange capacities, they can still be considered appropriate for liner applications, if other stipulated geotechnical parameters such as low hydraulic conductivity, adequate plasticity, and chemical stability are satisfactorily met.

3.4. Suitability as landfill liner materials

The geotechnical properties of the lateritic soils studied (QDLS, MDLS, and CDLS) were assessed against commonly used criteria for compacted landfill liners, based on established guidelines and previous studies [23,33–35,37,42]. Compliance with the key requirements is summarized in Table 4.

Overall, the lateritic soils meet some, but not all, of the standard criteria for compacted liners. They satisfy requirements related to maximum particle size, liquid limit, and plasticity index, indicating good workability and a low risk of shrinkage. However, several samples do not meet the recommended thresholds for clay and fines content or cation exchange capacity. These limitations are mainly due to relatively high sand content and the dominance of kaolinite. Based on the matrix classification of [37], most samples fall into the categories of "useful" or "unsuitable without treatment." This suggests that soil modification, such as blending with bentonite, or very careful field compaction may be required to consistently achieve the target hydraulic conductivity of less than 10^{-7} cm/s. Even with these constraints, the combination of appreciable fines content, moderate plasticity, and low shrinkage potential supports the use of these locally available soils as landfill liner materials in tropical regions, particularly when incorporated into composite liner systems or used with appropriate engineering controls.

3.5. Sorption characteristics of the lateritic soils

Table 5a, b, c, and d present the adsorption efficiency (% Rem), equilibrium concentrations (C_{eq}), amount of heavy metal adsorbed at equilibrium (Q_{eq}) and equilibrium desorption quantities (Q_{de}) for each

Table 4
Comparison of the Studied Lateritic Soils with Common Geotechnical Criteria for Landfill Liners.

Criterion	Recommended Threshold/ Source	QDLS	MDLS	CDLS	Overall Compliance/Notes
Maximum particle size	< 25 mm [32]; < 50 mm [33]	Meets	Meets	Meets	All soils well below limits; no coarse gravel issues.
Clay content (%)	≥ 15% [34]; ≥ 25% [35]; ≥ 30% [36]	Does not meet most	Does not meet most	Does not meet most	None exceed 50%; below higher thresholds → may require treatment for low k assurance.
Fines content (%)	> 20% [36]; > 30% [32]; > 50% [35]	Partial (meets lower)	Partial (meets lower)	Partial (meets lower)	Substantial fines present but high sand with coarser texture, potential higher permeability.
Majer et al. [37] matrix	"Useful" or better preferred	Useful / Unsuitable w/o treatment	Useful / Unsuitable w/o treatment	Useful / Unsuitable w/o treatment	Most samples "useful" to "unsuitable without treatment" due to sand content.
Liquid limit (%)	≥ 30% [34]; < 90% [42]	Meets	Meets	Meets (one high)	Exceeds minimum; below upper limit → good workability.
Plasticity index (%)	10–30% [43]; < 35% for low shrinkage [33]	Meets	Meets	Meets	Average < 35%; minimal shrinkage risk.
CEC (meq/ 100 g)	≥ 10 often referenced [36]	Below/close	Below/close	Below/close	Low-moderate (kaolinitic); acceptable if other parameters (low k, plasticity) met.

Table 5a
Percentage removal efficiency of heavy metal by lateritic soils at different initial concentrations.

LS	CI (mg/ L)	Adsorption Efficiency (%)				
		Cd	Cr	Cu	Mn	Pb
MDLS	10	48.67 ± 0.10	24.74 ± 0.20	33.00 ± 0.06	49.72 ± 0.04	32.81 ± 0.04
	25	75.33 ± 0.20	65.89 ± 0.01	33.15 ± 0.01	63.25 ± 0.01	45.66 ± 0.02
	50	85.34 ± 0.04	81.38 ± 0.00	38.27 ± 0.02	68.71 ± 0.007	64.29 ± 0.02
	75	87.96 ± 0.007	80.96 ± 0.01	23.31 ± 0.01	75.90 ± 0.007	75.59 ± 0.02
	100	88.80 ± 0.01	84.73 ± 0.007	41.26 ± 0.01	57.95 ± 0.007	63.83 ± 0.03
QDLS	10	76.00 ± 1.00	18.65 ± 0.03	38.57 ± 0.20	34.75 ± 0.07	37.62 ± 0.03
	25	78.33 ± 0.02	58.50 ± 0.007	49.82 ± 0.08	19.91 ± 0.007	59.51 ± 0.007
	50	78.84 ± 0.007	73.48 ± 0.007	69.77 ± 0.00	25.50 ± 0.00	40.27 ± 0.04
	75	85.00 ± 0.007	79.84 ± 0.007	69.99 ± 0.007	31.99 ± 0.007	56.52 ± 0.00
	100	83.10 ± 0.007	82.82 ± 0.00	66.83 ± 0.01	41.48 ± 0.007	37.35 ± 0.00
CDLS	10	34.86 ± 0.10	37.26 ± 0.60	32.61 ± 0.007	30.19 ± 0.09	32.36 ± 0.04
	25	41.57 ± 0.04	30.44 ± 0.20	52.23 ± 0.02	38.58 ± 0.02	41.37 ± 0.01
	50	56.74 ± 0.05	22.14 ± 0.08	51.63 ± 0.04	26.11 ± 0.04	34.12 ± 0.007
	75	60.99 ± 0.08	34.95 ± 0.06	46.39 ± 0.007	36.12 ± 0.06	53.52 ± 0.01
	100	58.51 ± 0.01	41.62 ± 0.09	50.29 ± 0.007	51.60 ± 0.01	45.51 ± 0.007

CI (mg/L): Initial concentration, LS: Lateritic soil, MDLS: migmatite derived lateritic soil; QDLS: quartzite derived lateritic soil, CDLS: Charnokite derived lateritic soil

Table 5b
Equilibrium concentration (C_{eq}) of heavy metals in the lateritic soils.

LS	CI (mg/ L)	C_{eq} (mg/L)				
		Cd	Cr	Cu	Mn	Pb
MDLS	10	5.13 ± 0.01	7.53 ± 0.02	6.70 ± 0.006	5.03 ± 0.004	6.72 ± 0.004
	25	6.17 ± 0.05	8.53 ± 0.004	16.71 ± 0.003	9.19 ± 0.003	13.59 ± 0.006
	50	7.33 ± 0.02	9.31 ± 0.003	30.87 ± 0.008	15.65 ± 0.004	17.86 ± 0.010
	75	9.03 ± 0.00	14.28 ± 0.006	57.52 ± 0.008	18.08 ± 0.005	18.31 ± 0.02
	100	11.20 ± 0.01	15.27 ± 0.01	58.74 ± 0.02	42.06 ± 0.004	36.17 ± 0.03
QDLS	10	2.40 ± 0.10	8.14 ± 0.003	6.14 ± 0.02	6.53 ± 0.007	6.24 ± 0.003
	25	5.42 ± 0.005	10.38 ± 0.002	12.55 ± 0.02	20.02 ± 0.001	10.12 ± 0.002
	50	10.58 ± 0.006	13.26 ± 0.004	15.12 ± 0.001	37.25 ± 0.001	29.87 ± 0.02
	75	11.25 ± 0.009	15.12 ± 0.002	22.51 ± 0.006	51.01 ± 0.003	32.61 ± 0.002
	100	16.91 ± 0.01	17.18 ± 0.003	33.17 ± 0.01	58.52 ± 0.003	62.65 ± 0.005
CDLS	10	6.51 ± 0.01	6.27 ± 0.06	6.74 ± 0.0007	6.98 ± 0.009	6.76 ± 0.004
	25	14.61 ± 0.01	17.39 ± 0.04	11.94 ± 0.005	15.36 ± 0.006	14.66 ± 0.004
	50	21.63 ± 0.02	38.93 ± 0.04	24.19 ± 0.02	36.95 ± 0.02	32.94 ± 0.004
	75	29.26 ± 0.06	48.79 ± 0.05	40.21 ± 0.006	47.91 ± 0.04	34.86 ± 0.01
	100	41.49 ± 0.02	58.38 ± 0.09	49.72 ± 0.01	48.40 ± 0.01	54.50 ± 0.006

CI (mg/L): Initial concentration, LS: Lateritic soil, MDLS: migmatite derived lateritic soil; QDLS: quartzite derived lateritic soil, CDLS: Charnokite derived lateritic soil

soil type and heavy metal. Fig. 6 presents the adsorption isotherms, showing the relationship between the equilibrium concentration of each heavy metal in solution and the corresponding quantity adsorbed per gram of soil. The adsorption behavior of heavy metals in the lateritic soils was markedly influenced by the underlying parent rock, the specific heavy metal species, and the initial concentration (C_i) of the metal solution.

Across all the lateritic soil types, an overall trend of increased adsorption efficiency with increasing initial concentration (C_i) was observed. However, copper adsorption deviated from this trend, exhibiting lower uptake at certain higher concentrations (Table 5a). Cadmium consistently displayed the highest removal efficiency across all the lateritic soil, with average values ranging from 34.90% in charnockite derived lateritic soil (CDLS) at 10 mg/L to 88.80% in migmatite derived lateritic soil (MDLS) at 100 mg/L. Chromium and copper also showed notable removal trends, especially in MDLS and quartzite-derived soils (QDLS). For Cr, removal efficiencies reached up to 84.73% in MDLS and 82.82% in QDLS, while Cu removal ranged between 23.31% and 41.26% in MDLS and between 38.60% and 69.99% in QDLS. However, Cu exhibited a decline in adsorption at higher concentrations, particularly in CDLS and QDLS, which may be attributed to adsorption site saturation or competitive sorption dynamics. In contrast, Mn and Pb generally exhibited lower and more varying adsorption efficiencies. Pb removal varied from 32.81% to 75.59% in MDLS but dropped significantly in QDLS and CDLS, where Mn and Pb achieved

Table 5c
Adsorption capacity (Q_{eq}) of heavy metals in lateritic soils.

LS	CI (mg/L)	Adsorption Capacity (mg/g)				
		Cd	Cr	Cu	Mn	Pb
MDLS	10	0.097 ± 0.00	0.049 ± 0.0007	0.066 ± 0.00	0.0995 ± 0.0007	0.066 ± 0.00
	25	0.377 ± 0.0007	0.329 ± 0.0007	0.166 ± 0.00	0.316 ± 0.00	0.228 ± 0.00
	50	0.853 ± 0.0007	0.814 ± 0.00	0.380 ± 0.00	0.687 ± 0.00	0.643 ± 0.00
	75	1.319 ± 0.00	1.214 ± 0.00	0.350 ± 0.00	1.138 ± 0.00	1.134 ± 0.00
	100	1.776 ± 0.00	1.695 ± 0.0007	0.825 ± 0.00	1.159 ± 0.00	1.277 ± 0.0007
QDLS	10	0.152 ± 0.003	0.037 ± 0.00	0.077 ± 0.00	0.069 ± 0.0007	0.075 ± 0.00
	25	0.392 ± 0.00	0.292 ± 0.0007	0.249 ± 0.00	0.100 ± 0.00	0.298 ± 0.0007
	50	0.788 ± 0.00	0.735 ± 0.00	0.698 ± 0.00	0.255 ± 0.00	0.403 ± 0.0007
	75	1.275 ± 0.00	1.198 ± 0.00	1.050 ± 0.00	0.480 ± 0.00	0.848 ± 0.00
	100	1.662 ± 0.00	1.656 ± 0.00	1.337 ± 0.0007	0.830 ± 0.0007	0.747 ± 0.00
CDLS	10	0.070 ± 0.00	0.075 ± 0.0007	0.065 ± 0.00	0.060 ± 0.0007	0.065 ± 0.00
	25	0.210 ± 0.00	0.152 ± 0.0007	0.260 ± 0.00	0.193 ± 0.00	0.207 ± 0.00
	50	0.570 ± 0.0007	0.220 ± 0.0007	0.520 ± 0.0007	0.261 ± 0.00	0.341 ± 0.00
	75	0.920 ± 0.001	0.520 ± 0.0007	0.696 ± 0.00	0.542 ± 0.0007	0.803 ± 0.00
	100	1.170 ± 0.00	0.830 ± 0.002	1.006 ± 0.00	1.032 ± 0.00	0.910 ± 0.00

CI (mg/L): Initial concentration, LS: Lateritic soil, MDLS: migmatite derived lateritic soil; QDLS: quartzite derived lateritic soil, CDLS: Charnokite derived lateritic soil

Table 5d
Desorption capacity of heavy metals in lateritic soils.

LS	CI (mg/L)	Desorption Capacity (mg/g)				
		Cd	Cr	Cu	Mn	Pb
MDLS	10	0.083 ± 0.00	0.027 ± 0.0007	0.022 ± 0.00	0.074 ± 0.00	0.038 ± 0.00
	25	0.343 ± 0.0007	0.273 ± 0.00	0.140 ± 0.00	0.274 ± 0.00	0.180 ± 0.00
	50	0.779 ± 0.00	0.739 ± 0.00	0.279 ± 0.0007	0.626 ± 0.00	0.594 ± 0.00
	75	1.233 ± 0.0007	1.086 ± 0.00	0.225 ± 0.00	1.015 ± 0.00	1.020 ± 0.00
	100	1.664 ± 0.00	1.556 ± 0.00	0.674 ± 0.0007	1.005 ± 0.00	1.131 ± 0.0007
QDLS	10	0.151 ± 0.003	0.036 ± 0.00	0.070 ± 0.0007	0.069 ± 0.0007	0.064 ± 0.00
	25	0.376 ± 0.01	0.278 ± 0.01	0.222 ± 0.01	0.088 ± 0.01	0.273 ± 0.01
	50	0.781 ± 0.00	0.727 ± 0.00	0.673 ± 0.0007	0.245 ± 0.00	0.385 ± 0.0007
	75	1.273 ± 0.0007	1.186 ± 0.00	0.985 ± 0.00	0.468 ± 0.00	0.821 ± 0.00
	100	1.656 ± 0.00	1.624 ± 0.00	1.256 ± 0.0007	0.810 ± 0.00	0.698 ± 0.00
CDLS	10	0.065 ± 0.00	0.073 ± 0.0007	0.062 ± 0.00	0.052 ± 0.00	0.058 ± 0.00
	25	0.201 ± 0.00	0.145 ± 0.0007	0.254 ± 0.0007	0.179 ± 0.00	0.199 ± 0.00
	50	0.560 ± 0.0007	0.214 ± 0.0007	0.508 ± 0.00	0.247 ± 0.00	0.332 ± 0.00
	75	0.904 ± 0.001	0.508 ± 0.001	0.687 ± 0.00	0.524 ± 0.0007	0.794 ± 0.00
	100	1.142 ± 0.0007	0.796 ± 0.002	0.996 ± 0.00	1.004 ± 0.0007	0.901 ± 0.00

CI (mg/L): Initial concentration, LS: Lateritic soil, MDLS: migmatite derived lateritic soil; QDLS: quartzite derived lateritic soil, CDLS: Charnokite derived lateritic soil

removals as low as 19.91% and 30.20%, respectively. QDLS also showed limited sorption for these two metals, suggesting the possible influence of lower CEC or fewer high-affinity binding sites.

The equilibrium concentration (C_{eq}) of heavy metals remaining in solution after sorption by soil is an indicator of the soil's retention capacity [25]. Lower C_{eq} values suggest higher sorption efficiency, while higher values imply weaker metal retention by the soil matrix. Generally, lower C_{eq} were recorded at lower initial concentrations, indicating that the soils effectively adsorbed most of the metal ions present in the solution (Table 5b). This trend is attributed to the abundance of high-affinity sorption sites at low contaminant levels, where the ratio of metal ions to available surface area is small. These sites, characterized by moderate-to-strong bonding energies, enable efficient uptake of metals [49]. However, as the initial concentration increases, high-energy sites become progressively saturated, and adsorption is governed by lower affinity sites or becomes limited by the availability of active sites, resulting in elevated C_{eq} values and reduced retention efficiency.

While some metals, such as cadmium in QDLS, retained strong affinity even at higher concentrations, others such as copper in MDLS and manganese in CDLS soils showed diminished sorption capacity, as reflected by their elevated C_{eq} values. The extent of metal retention at higher concentrations varied depending on both the type of heavy metal and the parent material of the lateritic soils (Table 5b). QDLS demonstrated the strongest retention for cadmium, with the lowest C_{eq} values (2.40–16.91 mg/L), suggesting high affinity across the concentration range. In contrast, manganese (6.53–58.52 mg/L) and lead (6.24–62.65 mg/L) exhibited higher C_{eq} values, indicating relatively weaker retention. Chromium and copper showed moderate equilibrium concentrations, ranging from 8.14 to 17.18 mg/L and 6.14–33.17 mg/L, respectively. MDLS also showed strong retention for cadmium (C_{eq}: 5.14–11.21 mg/L). However, chromium (7.53–15.27 mg/L) exhibited weaker affinity, and copper's C_{eq} rose sharply at higher concentrations (up to 58.74 mg/L), reflecting diminished sorption capacity. Manganese and lead showed moderate retention, with maximum C_{eq} values of 42.06 mg/L and 36.17 mg/L, respectively. CDLS consistently recorded the highest C_{eq} values across most metals, particularly for chromium (6.27–58.38 mg/L) and manganese (6.98–48.40 mg/L), indicating limited sorption efficiency compared to the other lateritic soil types.

The equilibrium adsorption capacity (q_{eq}) provides as a direct measure of the soil's ability to retain heavy metals. Similar to the C_{eq}, q_{eq} is influenced by the initial metal concentration and the physicochemical properties of the soil matrix. In general, q_{eq} increased with increasing equilibrium and initial concentrations across all metals and soil types (Table 5c and Fig. 7), a trend characteristic of sorption systems governed by site saturation, as described by Langmuir and Freundlich isotherms. The q_{eq} vs. C_{eq} plots (Fig. 6) reveal distinct adsorption patterns for each lateritic soil type, reflecting their varying sorption capacities. These differences are attributed to inherent variations in mineral composition, specific surface area, and organic matter content.

Among the three lateritic soils, QDLS and MDLS consistently demonstrated higher q_{eq}, confirming their relatively stronger affinity for heavy metals and making them more effective natural adsorbents. In contrast, CDLS exhibited the lowest q_{eq} values across most metals, suggesting a limited availability of effective sorption sites or a less favorable mineralogical property. Cadmium exhibited the highest q_{eq} values in QDLS and MDLS, indicating a strong and consistent affinity across varying concentrations. On the other hand, copper in MDLS and chromium in CDLS showed reduced adsorption capacities, particularly at higher concentrations likely due to the result of saturation of high-affinity sites, after which further adsorption occurs only on less efficient surfaces. In MDLS, cadmium demonstrated the highest retention

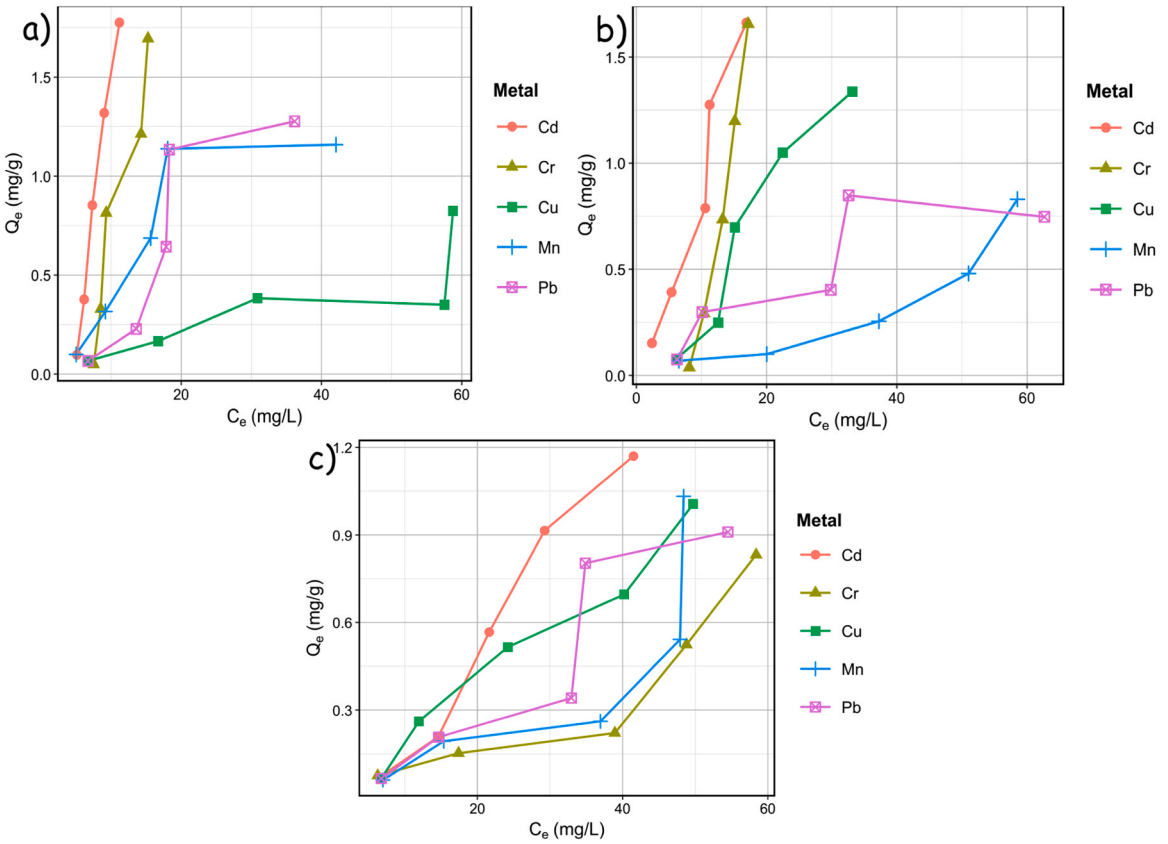


Fig. 6. Adsorption Isotherms of the heavy metals removed from solution per gram of the lateritic soil a) MDLS, migmatite derived lateritic soil b) QDLS, quartzite derived lateritic soil c) CDLS, charnokite derived lateritic soil.

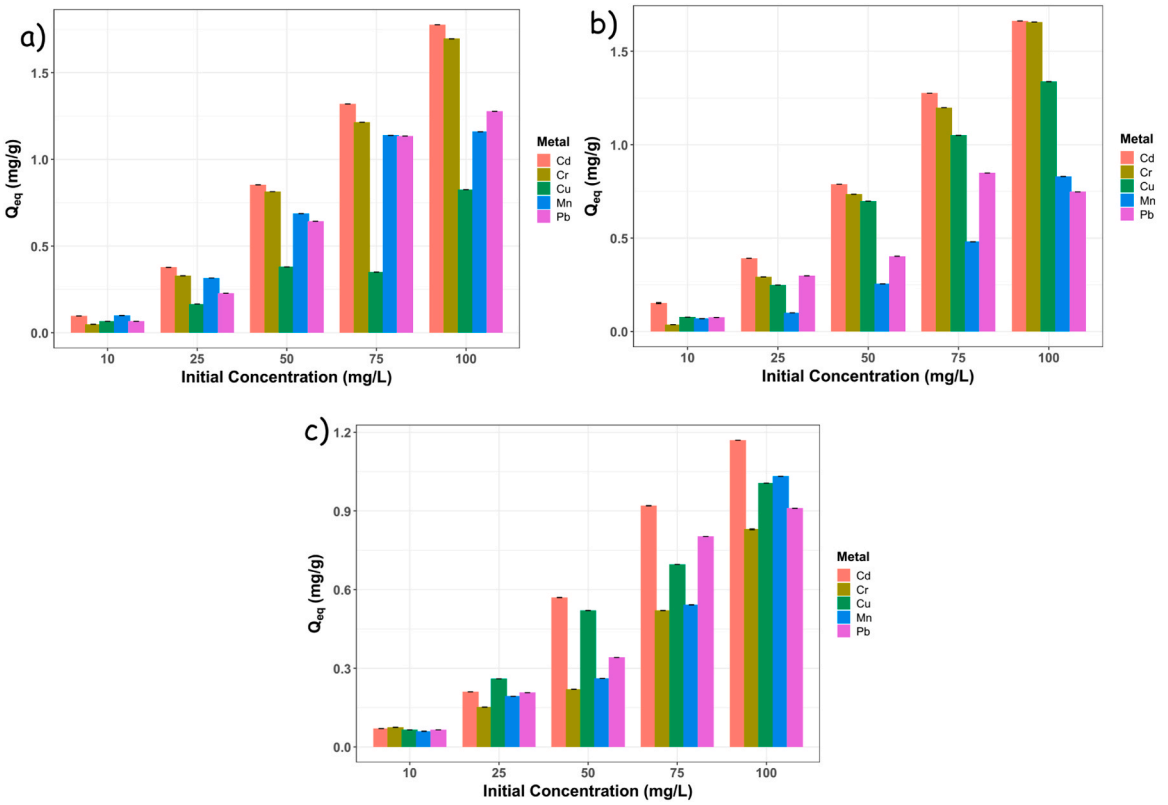


Fig. 7. Plot of the maximum adsorption capacity of the lateritic soil samples for each heavy metal. a) MDLS: migmatite derived lateritic soil b) QDLS: quartzite derived lateritic soil c) CDLS: Charnokite derived lateritic soil.

with q_{eq} values ranging from 0.097 mg/g at 10 mg/l to 1.776 mg/g at 100 mg/l. Chromium followed with values between 0.049 and 1.695 mg/g, while lead and manganese exhibited moderate adsorption, peaking at 1.277 mg/g and 1.159 mg/g, respectively. Notably, copper showed a decline in q_{eq} at higher concentrations, peaking at 1.010 mg/g at 50 mg/L but decreasing to 0.469–0.520 mg/g at 75–100 mg/L, suggesting a drop in sorption efficiency at elevated metal loads. QDLS also showed strong cadmium retention, with q_{eq} ranging from 0.152 mg/g to 1.662 mg/g. Copper performed comparably well, increasing from 0.077 mg/g to 1.337 mg/g. Chromium had moderate q_{eq} values (0.037–1.656 mg/g), while manganese and lead showed weaker adsorption, ranging from 0.069 to 0.830 mg/g and 0.075–0.848 mg/g, respectively. In CDLS, adsorption capacity was generally lower. Cadmium remained the most retained metal (q_{eq}:0.070–1.170 mg/g), while chromium exhibited the lowest values (0.075–0.832 mg/g). Copper, manganese, and lead had moderate q_{eq} values, with maximum values at 100 mg/L of 1.006 mg/g, 1.032 mg/g, and 0.910 mg/g, respectively.

The selective sequence of heavy metal adsorption by the lateritic soils, based on their maximum adsorption capacities at an initial concentration of 100 mg/L, is illustrated in Figure 7Figure 7. The selectivity sequences for the MDLS, QDLS, and CDLS are Cd > Cr > Pb > Mn > Cu, Cd > Cr > Cu > Pb > Mn, and Cd > Mn > Cu > Pb > Cr, respectively. Across all soils, Cd exhibited the strongest sorption, while Cu consistently showed the weakest. This limited uptake of Cu may be attributed to the acidic nature of the lateritic soils, which diminishes its binding affinity [53]. The preferential sorption of metals with larger ionic radii, such as Pb and Cd, over smaller ions like Cr^{3+} and Mn^{2+}, further shows the influence of ionic size, valence, and mineralogical interactions. The high sorption of Cr in QDLS is likely due to Cr^{3+}'s higher valence enhancing electrostatic interactions [54]. It is important to note that this study investigated only trivalent chromium (Cr^{3+}, the predominant and less mobile form under the reducing conditions of landfill liners [55]. The behavior of hexavalent chromium (Cr(VI)), which is more toxic and mobile under oxidizing conditions, may differ significantly and warrants separate investigation for comprehensive risk assessment. The strong retention of Cd, Pb, and Mn is attributed to the presence of goethite and kaolinite, both effective sorbents for divalent and trivalent metal ions [56,57].

The maximum adsorption capacities and related isotherm parameters obtained from fitting the experimental data to Freundlich and Langmuir models are summarized in Table 6. The goodness-of-fit values (R^2) across both models were generally high, with 97% of the lateritic soil samples displaying R^2 values ≥ 0.70, indicating that the sorption of trace metals could be adequately described by both Freundlich and Langmuir isotherm equations. This dual applicability aligns with previous studies on tropical soils [14,58] and is reflective of the complex and heterogeneous nature of sorption processes driven by competitive interactions and diverse soil mineralogy [59].

The Freundlich constants, KF and 1/n, provide insights into the adsorption intensity and surface heterogeneity, respectively. Across the parent rock types, KF values varied significantly, ranging from 8.522 mg/l in MDLS for Cd to as high as 87.91 mg/l in CDLS for Cr. Generally, higher KF values were observed in CDLS for most metals, implying greater overall adsorption capacity in Freundlich terms. The heterogeneity factor (1/n) remained within the favorable range ($0 < 1/n < 1$) for nearly all cases, indicating effective sorption with heterogeneous surface characteristics. Only Cu in migmatite-derived lateritic soil exhibited a 1/n value approaching 1 (1/n = 0.9038), suggesting near-linear adsorption behavior. No case exceeded 1, thereby ruling out cooperative adsorption [60]. Values of n ranged from 1.12 to 5.28, indicating both normal and cooperative adsorption behavior. Remarkably, n values exceeded 1 in all cases, except marginally for Cr in charnockite-derived lateritic soil (n = 1.12), confirming that the amount of adsorbed metals increased more rapidly than their concentration in solution. QDLS showed the best Freundlich model fit for Cd ($R^2 = 0.98$), whereas CDLS yielded the best fits for Pb ($R^2 = 0.93$) and Cu ($R^2 = 0.94$).

Table 6
Sorption isotherm parameters of heavy metals in the lateritic soils.

		Cd	Cr	Cu	Mn	Pb
Freundlich Isotherm Parameters						
MDLS	1/n	0.2485	0.1895	0.9038	0.7002	0.4503
	n	4.025	5.278	1.106	1.428	2.221
	KF	8.522	12.092	87.228	23.164	23.639
	R^2	0.89	0.72	0.89	0.84	0.85
QDLS	1/n	0.7833	0.1910	0.5201	0.7952	0.8623
	n	1.28	5.24	1.92	1.26	1.16
	KF	10.98	14.51	23.31	85.93	50.6
	R^2	0.98	0.95	0.93	0.85	0.80
CDLS	1/n	0.6052	0.8914	0.7504	0.7327	0.7393
	n	1.65	1.12	1.33	1.36	1.35
	KF	33.73	87.91	44.68	62.93	53.02
	R^2	0.98	0.87	0.94	0.87	0.93
Langmuir Isotherm Parameters						
MDLS	q_{max}	8.934	11.671	1180.073	28.314	25.804
	KL	12.886	34.64	0.087	2.113	5.285
	R^2	0.74	0.51	0.99	0.94	0.95
QDLS	q_{max}	33.378	14.21	26.908	-205.266	48.732
	KL	0.509	34.883	3.79	-0.531	1.881
	R^2	0.996	0.78	0.96	0.84	0.84
CDLS	q_{max}	42.428	-100.492	41.723	109.411	74.042
	KL	2.575	-0.831	2.846	1.126	1.523
	R^2	0.991	0.945	0.908	0.964	0.976

KL: Langmuir constant; q_{max}: maximum adsorption capacities; 1/n: Freudlich constant; KF: Freudlich sorption constant; R^2: Goodness-of-ft; MDLS: Migmatite Derived Lateritic Soil; QDLS: Quartzite Derived Lateritic Soil; CDLS: Charnokite Derived Lateritic Soil

Overall, the results indicate favorable adsorption across all soil types, with variations in heterogeneity influenced by parent rock mineralogy and metal species.

The Langmuir isotherm, which assumes monolayer adsorption onto a homogeneous surface with finite adsorption sites, was applied to evaluate the maximum adsorption capacity (q_{max}) and binding affinity (KL) of the studied lateritic soils. The model demonstrated varying degrees of fit across soil-metal combinations, with over 60% of the systems yielding strong correlations ($R^2 > 0.90$), indicating acceptable performance for some metal soil pairs under controlled conditions. However, for certain metal–soil pairs, the fundamental assumptions of the Langmuir model were not met. Langmuir-derived q_{max} values showed significant variability across metals and the soil type. For instance, Cu exhibited the highest maximum adsorption capacity in MDLS ($q_{max} = 1180.07$ mg/g), though this may be an outlier influenced by non-linear behavior and should be interpreted with caution. More conservative and physically realistic q_{max} values were recorded in QDLS and CDLS, ranging between 26.91 mg/g and 74.04 mg/g for most metals. KL values, which reflect the binding affinity of metals to the adsorbent surface, were highest for Cr in QDLS (KL = 34.88 L/mg) and Pb in MDLS (KL = 5.29 L/mg), signifying strong binding strength.

Negative Langmuir parameters, such as those observed for Mn in QDLS ($q_{max} = -205.27$ mg/g; KL = –0.531 L/mg) and for Cr in CDLS, are physically non-meaningful and indicate a poor fit of the Langmuir model to those particular datasets rather than experimental error. Such outcomes are a known limitation of the Langmuir model, particularly when applied in linearized form to sorption data obtained from mineralogically heterogeneous materials [61]. The lateritic soils investigated in this study are characterized by complex surface chemistry dominated by kaolinite and iron/aluminum oxides, variable-charge sites, and competitive multi-metal interactions, all of which favor heterogeneous and non-ideal adsorption mechanisms that violate Langmuir assumptions.

Consequently, where Langmuir fitting produced extreme or negative q_{max} values, the Freundlich model was considered more representative of the sorption mechanism and was therefore emphasized in the interpretation. In these cases, sorption behavior is better described by the Freundlich isotherm, which does not assume surface homogeneity or

monolayer coverage. Consistent with this, the Freundlich model provided more reliable and physically meaningful fits across all soil–metal systems examined (e.g., for Mn in QDLS, $R^2 = 0.85$) (Table 6). Accordingly, Langmuir parameters for metal–soil combinations yielding negative q_{max} values were not used to infer adsorption capacity but are retained for completeness and comparative assessment of model performance.

Overall, the isotherm modeling indicates that the adsorption behavior of Cd, Cr, Cu, Mn, and Pb in the studied lateritic soils can be adequately described using equilibrium models, with the Freundlich isotherm providing the most consistent and physically meaningful representation across all soil–metal systems. While the Langmuir model produced acceptable fits for some combinations, its applicability was limited in cases where model assumptions were not satisfied. The estimated sorption capacities fall within ranges reported in the literature [14], although they are generally lower than values reported for some tropical soils [58]. This difference may be attributed to the dominance of kaolinitic clays, variable-charge mineral surfaces, and the acidic conditions characteristic of the present study area [16], which favor heterogeneous and non-ideal adsorption mechanisms.

To better explain these patterns, it is necessary to consider the mineral composition of the soils and the chemical nature of their reactive surfaces. Although detailed mineralogical analyses such as XRD or SEM-EDS were not performed, the interpretation of mineralogical control on metal sorption is supported by published studies of lateritic soils from the same geological setting and parent rocks in southwestern Nigeria [11,16]. These studies consistently identify kaolinite as the dominant clay mineral, with iron and aluminum oxides, especially goethite and hematite, playing a key role in controlling surface reactions/reactivity. The measured soil pH (4.6–6.7) and low to moderate cation exchange capacity (CEC; 4.6–14.4 meq/100 g) provide important context for the observed retention patterns or sorption selectivity. The low CEC values are typical of kaolinite-rich soils and indicate limited capacity for simple ion exchange, meaning that metal retention is mainly influenced by pH-dependent surface interactions [62]. Under the experimental conditions (pH 2.5–3.0), reactive sites on iron and aluminum oxides are expected to carry positive charge, which generally reduces electrostatic attraction of metal ions [63]. The retention of several metals even under strongly acidic conditions is consistent with the formation of relatively stable surface complexes, including possible inner-sphere complexation with Fe/Al oxide and kaolinite surfaces, as proposed in the literature [64]. However, direct spectroscopic evidence (e.g., XPS or EXAFS) would be required to confirm this mechanism definitively.

This framework helps explain differences in sorption behavior among the soils. For example, MDLS, characterized by lower CEC (4.55 meq/100 g) and lower pH (4.61–5.14), shows a selectivity sequence (Cd > Cr > Pb > Mn > Cu) consistent with dominant control by specific adsorption on iron-oxide-rich surfaces. In contrast, CDLS, with higher CEC (13.5–14.4 meq/100 g) and near-neutral pH (6.2–6.7), shows a modified sequence (Cd > Mn > Cu > Pb > Cr), suggesting that both specific adsorption and limited ion-exchange mechanisms may contribute [65]. The consistently strong retention of cadmium across all soils is likely linked to its chemical or ionic properties, which favor stable binding to oxide and clay edge sites under acidic conditions [66]. By comparison, copper shows lower retention at low pH, probably because competition from protons reduces its ability to bind to soil surfaces, despite its stronger affinity under less acidic conditions [67]. Overall, the observed selectivity sequences reflect the combined effects of soil pH, metal-specific behavior in solution, and surface reactions on kaolinite and iron and aluminum oxides. Variations in parent material and resulting mineral composition therefore play a central role in shaping metal retention in these lateritic soils [68].

The strongly acidic pH used in this study may underestimate metal retention compared with neutral conditions typical of mature landfill leachate. At older waste sites in southwestern Nigeria, leachate pH commonly ranges from 7 to 9, a condition that favors stronger metal binding to soil surfaces [69]. At the same time, the low salt content of the synthetic solutions may overestimate metal retention by reducing competition from common dissolved ions such as calcium, sodium, and magnesium. Considered together, these conditions provide a conservative test of metal retention. They are intended to reveal how lateritic soils may behave under acidic stress, rather than to represent average field conditions.

3.6. Desorption behavior of heavy metals in the lateritic soils

The desorption of the heavy metals from the adsorbed phase into the aqueous phase was examined to evaluate the reversibility of the sorption process in the lateritic soils. Table 5d presents the equilibrium desorption quantities (Q_{de}) across varying initial concentrations (C_i), while Fig. 8 illustrates the overall trends for each metal-soil combination.

The result revealed that Q_{de} increased proportionally with the adsorbed quantity (Q_{eq}), reflecting the expected relationship between sorption and desorption. This correlation was particularly evident for cadmium, chromium, and lead, where desorbed amounts closely followed increases in Q_{eq} with rising C_i (Fig. 8). For example, in MDLS, Cd desorption rose from 0.08 mg/g at $C_i = 10$ mg/L to 1.664 mg/g at $C_i = 100$ mg/L. Similar trends were observed in quartzite- and charnockite-derived soils, with Q_{de} values of 1.656 mg/g and 1.141 mg/g, respectively, at the highest concentration. At lower initial concentrations, desorption was minimal across all metals and soil types, likely due to the preferential occupation of high-energy adsorption sites, which are less susceptible to desorption [70]. As C_i increased, these high-energy sites became saturated, resulting in adsorption onto lower-energy, more labile sites, thereby facilitating greater desorption.

The amount of metal desorbed was consistently lower than the amount adsorbed in all lateritic soils and for all metal species, indicating partial rather than complete desorption. For instance, in CDLS at $C_i = 100$ mg/L, Pb adsorption reached 0.910 mg/g, while desorption was slightly lower at 0.901 mg/g, suggesting near-complete but not total reversibility. In contrast, QDLS retained more of the adsorbed metals after desorption, indicating stronger binding affinity. For example, Cd in QDLS had a Q_{eq} of 1.662 mg/g and a corresponding Q_{de} of 1.656 mg/g, again demonstrating substantial but incomplete reversibility.

The partial reversibility of sorption, especially in the case of Cd and Cr, suggests that while the lateritic soils exhibit good retention potential, their long-term performance as barriers will depend on external factors such as pH, ionic competition, and redox conditions. These findings are consistent with previous studies reporting incomplete desorption in natural clay-rich soils due to strong specific adsorption mechanisms and inner-sphere complexation [71,72]. The variability in Q_{de} across the lateritic soils and metals shows the role of mineralogical composition. Lateritic soils derived from migmatite and quartzite likely benefit from higher concentrations of kaolinite, which enhances retention of Cd, Cr, and Mn. On the other hand, the elevated desorption of Mn in CDLS suggests differences in clay mineral content and surface chemistry that affect metal-soil interactions [11].

The extent of hysteresis in the sorption-desorption of heavy metals (Cd, Cr, Cu, Mn, Pb) by the different lateritic soils was quantified using a hysteresis index (HI). For the Freundlich isotherm, HI was defined as the ratio of the desorption exponent (n_{desorb}) to the sorption exponent (n_{sorb}), i.e.

$$HI = \frac{n_{desorb}}{n_{sorb}}$$

This index, presented in Table 7, displays the reversibility of the sorption process, where HI values close to unity indicate high reversibility, and higher values indicating potentially greater favorability of desorption [73]. Desorption data fitted the Freundlich isotherm across all metals and soils, with R^2 values ranging from 0.69 to 0.98 (Table 8), confirming the model's applicability. The Freundlich exponent n

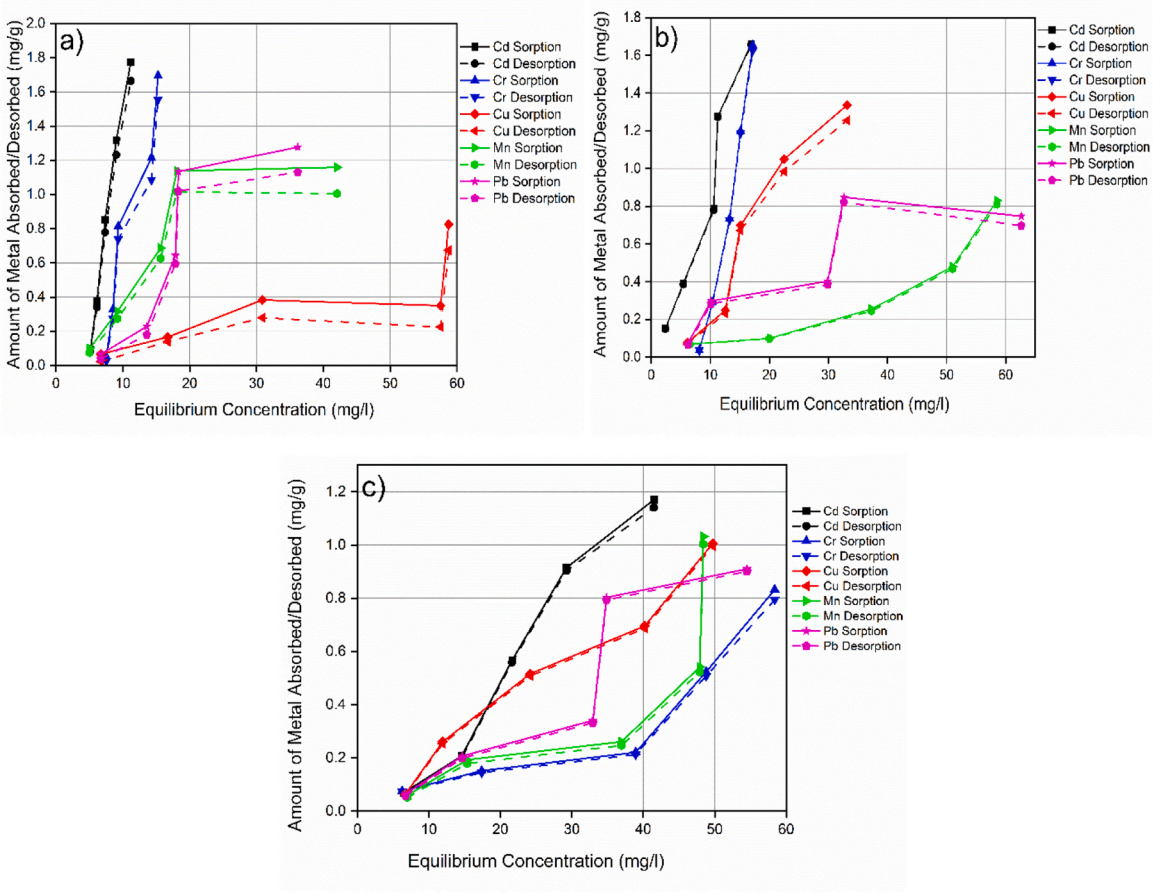


Fig. 8. Desorption and Adsorption Isotherms of the heavy metals a) MDLS: Migmatite Derived Lateritic Soil b) QDLS: Quartzite Derived Lateritic Soil c) CDLS: Charnokite Derived Lateritic Soil.

Table 7
Hysteresis Indices of Trace Metals in Lateritic Soil Samples and Their Retention Ranking.

Soil	Cd	Cr	Mn	Cu	Pb	Ranking of the metals by HI
MDLS	1.031	1.186	1.078	1.356	1.152	Cu > Cr > Pb > Mn > Cd
QDLS	1.000	1.004	1.000	1.016	1.052	Pb > Cu > Cr > Cd = Mn
CDLS	1.024	1.000	1.044	1.015	1.037	Mn > Pb > Cd > Cu > Cr

MDLS: Migmatite Derived Lateritic Soil; QDLS: Quartzite Derived Lateritic Soil; CDLS: Charnokite Derived Lateritic Soil

exceeded 1.00 in all the tests, indicating a non-linear relationship between initial metal concentrations and desorption, which is associated with favorable desorption conditions due to weaker metal-adsorbent bonding [11,74].

The Freundlich constant (KF) for desorption was generally slightly higher than for sorption, with increases observed in most cases, except for minor decreases in Cu (in MDLS) and Pb (in CDLS). This trend suggests enhanced desorption capacity, potentially due to shifts in site energy or competitive interactions, as evident in the divergence between sorption and desorption isotherms (Fig. 8). The n_{desorb} was equal to or greater than n_{sorb} in all cases, resulting in HI $\geq$ 1.000, which indicates no traditional positive hysteresis and suggests that desorption was at least as favorable as sorption, with some metals (e.g., Cu in MDLS, Pb in QDLS, Mn in CDLS) showing enhanced desorption potential [26]. HI values supported significant reversibility, with metal rankings varying by lateritic soil types Table 7.

The HI values, ranging from 1.000 to 1.356, reflect the desorption favorability of the metals from the lateritic soils, with higher values indicating greater release potential into the environment. For instance,

Table 8
Desorption isotherm parameters of heavy metals in the lateritic soils.

		Cd	Cr	Cu	Mn	Pb
Freundlich Isotherm Parameters						
MDLS	1/n	0.2409	0.1598	0.6661	0.6509	0.3910
	n	4.15	6.26	1.5	1.54	2.56
	KF	8.69	12.26	85.31	24.77	24.48
	R^2	0.89	0.69	0.85	0.83	0.85
QDLS	1/n	0.7809	0.1902	0.5122	0.7964	0.8178
	n	1.28	5.26	1.95	1.26	1.22
	KF	11.03	14.55	23.96	87.79	51.22
	R^2	0.98	0.95	0.92	0.85	0.79
CDLS	1/n	0.5933	0.8939	0.7399	0.7062	0.7129
	n	1.69	1.12	1.35	1.42	1.4
	KF	34	91.22	44.95	63.81	52.94
	R^2	0.98	0.86	0.94	0.87	0.93
Langmuir Isotherm Parameters						
MDLS	q_{max}	8.872	11.435	52.199	25.283	23.101
	KL	15.331	70.696	6.606	3.244	10.632
	R^2	0.73	0.48	0.95	0.92	0.94
QDLS	q_{max}	33.574	14.199	26.459	-192.681	42.707
	KL	0.509	35.932	4.259	-0.574	2.573
	R^2	0.996	0.78	0.96	0.83	0.83
CDLS	q_{max}	40.785	-96.692	40.785	88.799	64.475
	KL	2.901	-0.888	3.066	1.622	1.985
	R^2	0.99	0.94	0.91	0.96	0.97

KL: Langmuir constant; q_{max}: maximum adsorption capacities; 1/n: Freundlich constant; KF: Freudlich desorption constant; R^2: Goodness-of-ft; MDLS: Migmatite Derived Lateritic Soil; QDLS: Quartzite Derived Lateritic Soil; CDLS: Charnokite Derived Lateritic Soil

Cu in MDLS (HI = 1.356) and Cr in MDLS (HI = 1.186) exhibit the highest HI values, pointing to an increased risk of environmental release from permeable lateritic soil liners, necessitating careful design considerations to mitigate leachate migration. In contrast, metals with HI values at or near 1.000, such as Cd in QDLS (HI = 1.000) and Cr in CDLS (HI = 1.000), show lower relative desorption favorability, enhancing retention, which may be attributed to the high iron oxide and kaolinite content in these soils [57,75]. Mineralogical factors significantly influenced hysteresis, with migmatite's low Fe oxide and high silica content potentially contributing to the elevated HI values for Cu and Cr, indicating reduced retention capacity [11].

A Langmuir-based hysteresis index was assessed by comparing maximum desorption capacities ($q_{max,des}$) to sorption capacities ($q_{max,sorb}$). Where both values were positive (Table 6 and Table 8), HI ranged from 0.871 to 1.006, indicating near-complete reversibility. For example, Cd in QDLS exhibited an HI of 1.006, suggesting highly reversible adsorption–desorption equilibrium, consistent with monolayer Langmuir assumptions [74]. However, negative q_{max} values for Cr in (-96.692 mg/g), Mn in QDLS (-192.681 mg/g), and others (Table 8) suggest limitations in the Langmuir model for desorption, possibly due to multilayer adsorption or irreversible chemisorption [26]. The Langmuir constant (KL) for desorption exceeded sorption (e.g., Cu in MDLS: 6.606 vs. 0.087 L/mg), reflecting initial adsorption affinity. This aligns with studies showing that KL discrepancies may arise from kinetic limitations or site-specific binding [61].

3.7. Implications for compacted liner performance

Batch equilibrium tests use high liquid-to-solid ratios and constant mixing to ensure full contact between soil and solution. In contrast, compacted landfill liners operate under very different conditions, with low moisture content, high density, limited permeability, and contaminant movement controlled mainly by diffusion. As a result, sorption values from batch tests cannot be applied directly to field performance, but they offer useful first estimates of relative metal mobility and retention.

The distribution coefficients (Kd ≈ Qeq / Ceq) derived from this experiment provide insight into how strongly metals may be delayed during transport. Higher sorption generally means slower movement. The strong retention observed for metals such as Cd and Pb, especially in QDLS and MDLS, suggests a greater capacity to slow contaminant migration in compacted liners, where long contact times and limited pore water further restricts transport.

The hysteresis index values obtained in this study (1.000–1.356) indicate low to moderate reversibility of sorption. This implies that lateritic liners can act as effective sinks for contaminants under stable conditions, although some release may occur if pore water chemistry changes, such as under prolonged acidic conditions or shifts in redox state. Even so, the combined influence of strong initial retention and diffusion-controlled transport in compacted liners is expected to improve overall containment compared with the conditions represented in batch tests.

3.8. Comparison with previous studies and novel contributions of this work

To place the present findings in context, a comparison was made with recent studies on heavy metal sorption in lateritic soils from southwestern Nigeria, particularly those of [18] and [11]. The key similarities and differences are summarized in Table 9. While these previous studies provide valuable insights, they differ in important ways from the present work. For example, [11] incorporated detailed mineralogical characterization (e.g., XRD) and focused on competitive sorption at relatively higher concentrations (50–200 mg/L), whereas [18] examined competitive adsorption without evaluating desorption behavior.

Table 9
Comparison of Present Study with Previous Studies on Lateritic Soils for Heavy Metal Sorption.

Feature	Present Study	Daramola et al. [11]	Oderinde and Diagboya [18]
Parent materials	Quartzite, Migmatite, Charnockite	Porphyritic granite, Granite gneiss, Migmatite, Schist, Quartzite, Charnockite	Not specified (samples from Abeokuta & Emuhu, Nigeria)
Key mineralogy	Inferred (kaolinite, Fe/Al oxides from regional data)	Measured (XRD): Kaolinite, dickite, goethite, quartz	Not reported
Heavy Metals	Cd, Cr, Cu, Mn, Pb	Mn, Cd, Pb, Cu, Cr	Cd, Cr, Pb, Cu, Zn
Concentration range (mg/L)	10–100 (low, environmentally relevant)	50–200 (Higher / less typical of long-term exposure)	100–500 (Higher / less typical of long-term exposure)
Experimental system	Single-metal batch	Batch (single-metal stocks; described as "competitive")	Competitive (mixed-metal solutions)
pH conditions	2.5–3.0 (acidic, conservative)	2.5–3.0	Not specified
Isotherm models	Both Freundlich and Langmuir ($R^2 \geq 0.70$ for 97% of cases) – Freundlich more consistent	Langmuir (primary) and Freundlich ($R^2 \geq 0.70$ for 97% of cases)	Freundlich (for LAEM) and Langmuir (for LAAB)
Sorption performance	High Cd retention (up to 88.8%); Cu weakest	High Cd retention with Cu mainly the weakest	Strong Cu, Pb, Cr retention and Cd the weakest
Selectivity sequence	Parent-rock dependent	Parent-rock dependent	Cu > Pb > Cr > Zn > Cd (LAEM) and Cu > Cr > Pb ≫Zn > Cd (LAAB)
Desorption / hysteresis	Quantified in detail – HI range: 1.000 – 1.356 (Freundlich and Langmuir -based) but Freundlich gave the best results.	Quantified – HI range: 0.63 – 0.99 (Freundlich-based).	Not reported
Novel contribution	First systematic study at low (10–100 mg/L) concentrations for these soils. Provides HI > , 1 (reversibility), distribution coefficients (Kd), and clear ranking of parent-rock performance for liner selection.	First detailed mineralogical (XRD) + competitive sorption link for multiple parent rocks in the region. HI < , 1 (irreversibility).	Early competitive sorption study
Key practical implication	QDLS and MDLS recommended; Cd most retained, Cu least. Partial desorption under acidic conditions (HI >1) warns of potential remobilization.	Charnockite and granite-gneiss derived soils best; Cd and Pb most retained. High HI for Cr, Cd suggests release risk.	Laterite can retain Cr, Pb, Cu well; Zn and Cd more mobile.

In contrast, the present study introduces several complementary and practically relevant contributions. First, sorption–desorption behavior was investigated at lower, environmentally relevant concentrations (10–100 mg/L), which better reflect long-term leachate exposure conditions. Second, desorption was explicitly quantified using hysteresis indices (HI = 1.000–1.356), revealing low to moderate reversibility and indicating a potential risk of metal remobilization under acidic conditions. This contrasts with the lower HI values (0.63–0.99) reported by [11] and highlights the importance of considering desorption in liner

performance assessment.

In addition, this study provides distribution coefficients (K_d) and isotherm parameters derived under low-concentration conditions, offering more realistic first-order estimates of contaminant retardation in compacted liners. A further contribution is the direct comparison of soils derived from different parent rocks (quartzite, migmatite, and charnockite), which demonstrates that quartzite- and migmatite-derived soils combine favorable geotechnical properties with strong metal retention, despite relatively low cation exchange capacities.

Overall, the present work extends existing knowledge by integrating sorption, desorption, and geotechnical evaluation under conservative conditions, thereby providing more practical guidance for the selection and design of lateritic soil liners in tropical environments.

3.9. Limitations of the Study

Several limitations of this study should be acknowledged. First, the batch experiments employed single-metal systems, whereas actual landfill leachates contain complex mixtures of metals and organic/inorganic ligands that may influence sorption through competitive interactions and complexation. Similarly, mineralogical control was inferred from regional studies; however, direct characterization (e.g., XRD, FTIR, SEM-EDS) of the investigated soils was not conducted and would strengthen mechanistic interpretation. In addition, the 24 h equilibration time and high solution-to-soil ratio (1:20) represent well-mixed conditions that differ from the diffusion-dominated, low-moisture environment of compacted liners. Finally, the strongly acidic pH (2.5–3.0) was selected as a conservative scenario and does not capture the full range of landfill leachate conditions (pH 4–9) encountered in mature landfills. Consequently, sorption capacities may be underestimated, while desorption tendencies may be overestimated relative to neutral, multi-component field conditions.

4. Conclusion

This study evaluated the suitability of lateritic soils from southwestern Nigeria as landfill liners by examining their sorption and desorption characteristics for heavy metals at low concentrations (10–100 mg/L). The results revealed significant variability in the lateritic soil properties and their influence on contaminant retention due to differences in parent rock mineralogy and physicochemical characteristics. QDLS and MDLS exhibited superior adsorption capacities, particularly for cadmium and chromium, compared to CDLS, which showed lower retention due to limited high-affinity sorption sites. Sorption behavior was well-described by both Freundlich and Langmuir isotherm models, with high correlation coefficients ($R^2 \geq 0.70$), confirming their applicability to tropical lateritic soils. The Freundlich model generally provides better fits for heterogeneous sorption behavior while Langmuir modeling yielded reasonable estimates of maximum adsorption capacities, though some poor or negative fits for some metals, such as for Mn in QDLS, highlighted its limitations in certain cases. Desorption experiments showed partial reversibility, with hysteresis indices (1.000–1.356) indicating that metals like Cu and Cr are more prone to release under changing environmental conditions, posing challenges for long-term containment and requiring careful liner design to prevent leachate migration. The selective adsorption sequences (Cd > Cr > Pb > Mn > Cu for MDLS, Cd > Cr > Cu > Pb > Mn for QDLS, and Cd > Mn > Cu > Pb > Cr for CDLS) highlight the influence of parent rock mineralogy, with kaolinite and iron oxides playing key roles in metal retention.

The results of this study revealed the potential of lateritic soils especially those derived from quartzite and migmatite as effective landfill liner materials for reducing heavy-metal migration in tropical environments. The use of locally available lateritic soil offers a cost-effective and sustainable alternative to synthetic liners, reducing both construction costs and the impacts of material transport. In this way, the findings support more sustainable waste management and align with wider development goals, including protecting groundwater, strengthening waste containment systems, and making responsible use of local natural resources. However, the observed partial desorption under acidic conditions suggests that additional engineering measures, such as composite liner systems, may be needed to ensure long-term performance. Future studies should move beyond laboratory experiments to field-scale evaluations of long-term performance under varying environmental conditions. This should include testing across a wider range of pH (about 5–8.5) and ionic strength regimes (e.g., 10–500 mM with elevated electrolyte concentrations such as Na^+, Ca^{2+}, Cl^-, and NH_4^+), as this would better represent the variability of tropical landfill leachate. Such work would improve understanding of how pH and dissolved salts affect metal retention and would help guide the design of more effective and sustainable landfill liners.

CRediT authorship contribution statement

Olamide Elizabeth Onile-ere: Formal analysis. **Afolagboye Lekan Olatayo:** Writing – review & editing, Writing – original draft, Conceptualization. **Owoyemi Olubunmi Oluwadare:** Writing – review & editing, Formal analysis. **Kamoli Akinwale Rafiu:** Methodology, Investigation, Formal analysis. **Sunday Olabisi Daramola:** Writing – review & editing, Methodology.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

The data supporting the findings of this study are included within the article.

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