



Leachate Adsorption/Desorption Dynamics and their Influence on Dumpsites Soil Properties and Environmental Risk

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ABSTRACT: Landfill leachate, a contaminated liquid containing dissolved organic and inorganic matter, poses a significant environmental threat. This study investigated the interplay between leachate adsorption/desorption dynamics on dumpsites' soil properties and the consequent impact on environmental risk. The research focused on common cations and anions within the leachate composition and batch adsorption experiments was used to investigate the impact of leachate containing the ions on the key geotechnical soil properties like void ratio, porosity, degree of saturation, and dry density. Analysis of the leachate composition identified the presence of common cations (K^+ , Na^+ , Ca^{2+} , Mg^{2+}) and anions (SO_4^{2-} and Cl^-). The dumpsites' soil samples were characterized by low affinity or adsorption coupled with high desorption rate of these ions, which demonstrably influenced the geotechnical properties and environmental risk of the soils of the dumpsites. The increased mobility of these ions within the dumpsites' soil systems is potentially leading to contamination of surrounding soil and water resources. Therefore, this knowledge can inform strategies for mitigating environmental risks associated with leachate migration. The findings can guide approaches for leachate treatment, landfill design, and the selection of suitable cover materials to minimize contaminant movement and ensure long-term environmental protection. Hence, to maintain a balanced ecosystem, the study emphasizes the need for engineered landfills with a higher capacity for ions adsorption.

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Landfills are essential for managing solid waste, but leachate, a contaminated liquid produced by waste decomposition, can pose environmental risks. Leachate percolates through the landfill and interacts with the soil, influencing its geotechnical properties. Understanding how leachate components adsorb onto and desorb from the soil is crucial for predicting long-term landfill stability and potential environmental impacts. This study investigates the

adsorption/desorption dynamics of leachate within dumpsites located in Jos, Nigeria. Batch adsorption experiments will explore how leachate adsorption affects key soil properties, such as void ratio, porosity, degree of saturation, and dry density. By analyzing the leachate composition and its interaction with the soil, this research aims to elucidate the mechanisms by which leachate influences the geotechnical properties of dumpsites in Jos. The findings can contribute to the

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development of improved landfill management strategies to mitigate environmental risks associated with leachate migration (Wuave *et al.*, 2024a; Wuave *et al.*, 2024b). Transferring of material that involves a phase change of fluid to solid is termed as adsorption. It can be either physical or chemical in nature. Physical adsorption is governed by the van der Waals force of attraction (Babakura *et al.*, 2023; Adamu, 2021; Adamu *et al.*, 2019; Adamu *et al.*, 2018; Adamu *et al.*, 2017; Adamu *et al.*, 2016; Adamu and Anderson, 2015). It is similar to the condensation of gases to liquids. Any gas whose pressure is greater or a liquid with higher temperature tend to get adsorbed physically. Chemical adsorption involves a chemical force with which the gas or liquid molecules are held on to a solid surface (Babakura *et al.*, 2023; Adamu, 2021; Adamu *et al.*, 2019; Adamu *et al.*, 2018; Adamu *et al.*, 2017; Adamu *et al.*, 2016; Adamu and Anderson, 2015). It usually occurs at a temperature higher than that of physisorption and it is a comparatively slower process. It frequently entails an energy of activation for the chemical reaction to occur (Babakura *et al.*, 2023; Adamu, 2021; Adamu *et al.*, 2019; Adamu *et al.*, 2018; Adamu *et al.*, 2017; Adamu *et al.*, 2016; Adamu and Anderson, 2015). The most widely used adsorbent is activated carbon (Okparanma and Ayotamuno, 2008). The adsorption process is being widely used by various researchers for the removal of heavy metals from waste streams, and activated carbon has been frequently used as an adsorbent (Ahmed *et al.*, 2006; Akolo and Auta, 2006). Leachate samples collected from landfills showed variation in their type and concentration but their quantities exceed the permissible limit (Oliver *et al.*, 1999). Adsorption isotherm is an empirical relationship used to predict how much solute can be adsorbed by activated carbon (Babakura *et al.*, 2023; Adamu *et al.*, 2018; Adamu *et al.*, 2017; Adamu *et al.*, 2016; Steve *et al.*, 1998). The adsorption isotherm can be described as a graphical representation that depicts the correlation between the quantity of adsorbate adsorbed by a unit weight of adsorbent, such as activated carbon, and the residual amount of adsorbate present in a test medium at equilibrium. It serves to illustrate the partitioning of the adsorbable solute between the liquid and solid phases across a range of equilibrium concentrations (Babakura *et al.*, 2023; Adamu *et al.*, 2018; Adamu *et al.*, 2017; Adamu *et al.*, 2016; Ng *et al.*, 2002). The three well known isotherms are (a) Freundlich, (b) Langmuir, and (c) BET adsorption isotherm (Adamu *et al.*, 2017; Adamu *et al.*, 2016; Steve *et al.*, 1998). In this study, we undertook an investigation of a novel, environmentally friendly, and readily available agro-waste adsorbent for the purpose of adsorption. We conducted an examination of the impact of various parameters,

including pH, initial metal concentration, adsorption dosage, contact duration, and temperature. The successful exploration of utilizing indigenous microorganisms to alleviate the dissemination of contaminants such as heavy metals within the soil was a focal point of our investigation. Additionally, the incorporation of industrial and agricultural waste materials with pozzolanic characteristics as additives or admixture in compacted clay liners (CCLs) to facilitate the containment of contaminant migration within the soil was thoroughly explored (Eberemu *et al.*, 2017; Yohanna *et al.*, 2016; Osinubi *et al.*, 2014).

MATERIAL AND METHODS

The study was carried out on 6 dumpsites spread out from Jos North to Jos South to incidents caused by adsorption of anions and cations in dumping sites in the area.

Batch experiments and adsorption isotherms: Batch experiments were conducted in 250mL glass flasks to determine the adsorption isotherms of cations and anions onto the adsorbents. The percentage adsorbed was obtained from equation (1) where q_e is the quantity adsorbed (mg/g), V is the volume of solution (ml), M is the mass of soil (g), C_i is the initial concentration and C_e is the equilibrium concentration.

The solution volume (V) was kept constant. The amount of metal adsorbed per unit mass is calculated as

$$Q_e = (C_i - C_e) \frac{V}{m}, \quad (1)$$

Where C_i and C_e are the initial and equilibrium concentration (mg/L), m is the mass of the adsorbent (g) and V is the volume of the solution (mL). Percent metal ion removal (%MR) was calculated using the equation

$$\%MR = (C_i - C_e) / C_i * 100 \quad (2)$$

Varying the agitation time: Adsorption of was measured for a higher and lower initial concentration, 10 and 50 mg/l. A fixed volume (e.g., 50 mL) of one of the prepared target compound solutions (either 10 mg/L or 50 mg/L) to each Erlenmeyer flask containing the adsorbent and ensured that all flasks have the same initial volume. The flasks were placed in a shaking incubator and agitated at a constant speed of 200 rpm and maintained this speed throughout the experiment. At predetermined time intervals of 15 min, 30 min, 1 hour, 2 hours, a sample aliquot of 1 mL was collected from each flask using a syringe, which was centrifuged

to separate the supernatant containing the target compound.

Varying the initial concentration: Adsorption study was carried out by varying the initial concentration from 10mg/l to 50mg/l at a constant agitation time. After the designated reaction time, sample aliquots of 1 mL from each flask using a syringe were collected, centrifuged them to separate the supernatant containing the target compound.

Varying the pH: Sorption studies was conducted at a constant agitation time by varying the pH of the soil leachate mixture from 1 to 10 by adding 0.1M HCl solution and 0.1M NaOH to obtain lower and higher pH values, respectively. All experiments were conducted in duplicate, and the resulting average value was employed for subsequent calculations. The pH of the solution was determined using a HACH-pH meter.

RESULTS AND DISCUSSION

Batch adsorption or desorption test: Adsorption studies are carried out by varying several factors such as agitation time, initial concentration and pH as these are the important factors that influences adsorption in a dumpsite. Four cations and two anions namely, Potassium (K^+), Sodium (Na^+), Calcium (Ca^{2+}), Magnesium (Ma^{2+}) Sulphate (SO_4^{2-}) and Chloride (Cl^-) were considered because they are present in high concentrations in the six leachate samples used in this investigation (Table 1 to Table 6). Adsorption or desorption is a major process in the natural reduction of chemical contaminants in soils. Soil interaction with municipal soil waste (MSW) leachate medium is one of the key parameters governing the degree of contamination of underground water (Shackelford *et al.*, 2019; Adar and Bilgili, 2015). Batch Equilibrium Adsorption Test (BEAT) was used to evaluate the aptitude of the treated soil to absorb the contaminants present in the leachate in form of cations The effectiveness of the adsorption process has in general been taken to be a function of the molecules of various parameters in the contaminant solution, attractive forces of the atoms, surface area of the adsorbent and the chemical reaction between the adsorbate molecules and the adsorbent (McGechan and Lewis, 2002). This mechanism of adsorption with soil environment depend highly on the polarity of both adsorbent and adsorbate which is pH based. The polarity determines the molecules that can be adsorbed to the adsorbent.

Sorption/desorption performance assessment soil – leachate mixtures: The adsorption for cations (i.e. Potassium (K^+), Sodium (Na^+), Calcium (Ca^{2+}) and Magnesium (Ma^{2+}) and anions (i.e. Sulphate (SO_4^{2-}) and Chloride (Cl^-) considered in the study are

shown in Table 1 to Table 6. The positive isotherms indicate the existence of adsorption while negative isotherm suggests the occurrence of desorption of the ions considered. This is connected to the enzyme released by the microbes during hydrolysis that reduced the micro pores in the soil matrix and resulted in the reduced desorption of the ions. Bioactivities of the microbes (e.g., bioclogging) might also be responsible for the observed trend (Osinubi *et al.*, 2019; DeJong *et al.*, 2014; Francisca and Glatstein, 2010; DeJong *et al.*, 2010). The retardation factor (R_d) indicates the capacity of flow of cations and anions in the soil. The positive isotherms designate existence of adsorption, while negative isotherm suggests the occurrence of desorption of the ions studied (Boateng *et al.*, 2019; Shackelford, 1994).

Adsorption/desorption of potassium: The experimental results of the desorption isotherms for the cations and anions are presented in Table 1-6. The desorption of potassium (K^+) values from the soil-leachate mixtures across all leachate types (A-E) fall between -21 and 13. The adsorption/desorption isotherms for potassium (K^+) shown in Table 1, which is the usual occurrence for cations (Hong and Shackelford, 2017; Hong *et al.*, 2016). The data in Table 1 suggests that there is limited desorption of potassium (K^+) from the soil-leachate mixtures across all leachate types (A-E) and tested leachate suspension densities ($0 - 2.4 \times 10^9$ cells/ml). This is because most of the values fall between -21 and 13, which largely represent negative desorption or minimal change in K^+ concentration compared to the initial state. From the results, leachates A, C, and D are those leachates that show consistently negative or minimal desorption values across all densities, suggesting a strong affinity of the dumpsites soil for K^+ . Leachates B and E are those leachates that show only positive desorption values of 13, indicating a slight release of K^+ from the dumpsite soil at all densities. However, the lack of variation suggests a limited desorption capacity regardless of the leachate density. The possible explanations lie on the strong adsorption and limited desorption conditions. The negative desorption values might indicate strong adsorption of K^+ onto the soil particles. This could be due to factors like the presence of clay minerals with high cation exchange capacity (CEC) or specific binding sites for potassium. The batch equilibrium adsorption test (BEAT) conditions might not have been favorable for desorption. Factors like time, pH, or the presence of competing cations could be hindering the release of K^+ . Overall, though the results in Table 1 suggest limited desorption of potassium from the soil-leachate mixtures. However, further investigation is needed to fully understand the factors influencing K^+ desorption and its potential

implications for long-term contaminant mobility within the landfill environment and implying environmental risk associated with on the geotechnical properties of the dumpsites' soil of the study area. The retardation factors (*Rd*) values (not shown here) of -9.46, -9.7, 9.05, 9.04, 8.96 and 9.37 were recorded for soil treated with leachate suspension density of 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, respectively. The increase in retardation factor suggests the fact that desorption of K^+ reduced with increase in the population of the microbes. The equilibrium isotherm for K^+ had a strong Freundlich shape. The plotted desorption isotherms are all nonlinear in agreement with the findings that desorption or adsorption isotherms can be linear or non-linear (Shackelford, 1994). The recorded decrease

in the adsorption of K^+ could be attributed to the increase in pH of the mixtures. This may have triggered a drastic reduction in the percentage of K^+ adsorbed due to the weakening of electrostatic force of attraction between the oppositely charged adsorbate and adsorbent which ultimately led to the reduction in sorption capacity (Osim, 2017; Osinubi *et al.*, 2014). Accordingly, a strong correlation exists between the sorbed concentration and the equilibrium concentration denoted by strong coefficients of determination of 0.9967, 0.9759, 0.9759, 0.9673, 0.9759 and 0.9759 when dumpsite soil was treated with leachate suspension density of 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, respectively.

Table 1: Desorption isotherms for Potassium (K^+) of leachate Soil- mixtures during batch equilibrium adsorption test (BEAT) for different leachate.

	<i>Leachate</i> suspension density (cells/ml)					
Leachate	0	1.5×10^8	6.0×10^8	1.2×10^9	1.8×10^9	2.4×10^9
Leachate A	-21	-13	-13	-13	-17	-13
Leachate B	13	13	13	13	13	13
Leachate C	-5	-5	-13	-5	-5	-5
Leachate D	-17	-13	-13	-13	-13	-13
Leachate E	13	13	13	13	13	13

Adsorption/desorption of sodium: The desorption of sodium (Na^+) values from the soil-leachate mixtures across all leachate types (A-E) fall between -80 and 152. Table 2 shows contrasting desorption patterns for sodium (Na^+) depending on the leachate type (A-E) used in the batch equilibrium adsorption test (BEAT) with soil-leachate mixtures. The leachate suspension density (0 - 2.4×10^9 cells/ml) seems to have a limited influence on desorption in most cases. The adsorption isotherms for sodium (Na^+) shown in Table 2 is the usual occurrence for cations. The adsorbed and desorbed Na^+ ion values were in the ranges This is because most of the values fall between -80 and 152 mg/l for MSW leachates A, B, C, D and E, respectively, when soil was treated with leachate suspension density of 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, respectively using the regressed line, as reported in the literature (Hong and Shackelford, 2017; Hong *et al.*, 2016). From the results, leachates A and B exhibit a desorption trend, with Na^+ concentrations decreasing (positive values decrease) compared to the initial state (0) at all densities except the lowest (0 cells/ml). This suggests a release of sodium from the soil back into the leachate. Leachate C shows initial desorption followed by re-adsorption with increasing leachate suspension density. The initial decrease in Na^+ concentration suggests desorption, while the subsequent increase at higher densities indicates a reversal towards re-adsorption. Leachates D and E display consistent negative desorption values across all densities. This

suggests a strong affinity of the dumpsite soils for Na^+ or limited desorption under the test conditions, indicating low potential mobility of Na^+ ions through the leachate down the dumpsite soils profile. The varying desorption patterns across leachates might indicate differences in the initial adsorption strength of Na^+ onto the soils. Leachates A, B, and C might have resulted in weaker initial adsorption, facilitating desorption and thereby imposing environmental risk of the dumpsites soil. The presence of other cations in the leachate could be competing with Na^+ for binding sites on the soil particles. This competition might influence the observed desorption behavior. Similar to the observations for potassium (Table 1), the BEAT conditions might not have been optimal for desorption of Na^+ . Factors like time, pH, or the presence of competing cations could be hindering significant release. Overall, the results in Table 2 suggest that the desorption behavior of sodium varies depending on the leachate composition. Further investigation is needed to fully understand the factors influencing Na^+ desorption and its potential implications for contaminant mobility within the landfill environment and its associated environmental risk in accordance with the geotechnical properties of the dumpsites' soil. The retardation factor (not shown here) increased marginally with increase in leachate suspension density. Values of -15.57, -15.22, -13.42, -14.99, -13.98 and -12.83 were recorded for soil treated with suspension of 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml respectively. The recorded

increase in retardation factor presumed a reduction in desorbed Na^+ with increase in the microbial population in the treated soil. The plotted desorption isotherms are all non-linear in agreement with the findings reported in the literature (Shackelford and Daniel, 1991). However, the amount of Na^+ recorded could be regarded as being insignificant (Osinubi *et al.*, 2014), as it was reported that high concentration of

Na^+ in any given soil generally give rise to the dispersion of the soil particles. Thus high Na^+ concentration in compacted soil liners may impede negative impact on its performance. The results of this study are in agreement with the findings reported in the literature (Osinubi and Eberemu, 2009; McGregor, 1999).

Table 2: Desorption isotherms for Sodium (Na^+) of leachate Soil– mixtures during batch equilibrium adsorption test (BEAT) for different leachate

	<i>Leachate suspension density(cells/ml)</i>					
Leachate	0	0.15×10^8	6.0×10^8	1.2×10^9	1.8×10^9	2.4×10^9
Leachate A	116	96	96	84	92	92
Leachate B	112	112	108	104	88	88
Leachate C	152	152	128	136	132	124
Leachate D	-32	-48	-44	-56	-48	-64
Leachate E	-36	-64	-76	-72	-80	-100

Adsorption/desorption of calcium: Table 3 reveals intricate desorption patterns for calcium (Ca^{2+}) in the leachate-soil mixtures across various leachate types (A-E) and tested leachate suspension densities ($0 - 2.4 \times 10^9$ cells/ml) within the batch equilibrium adsorption test (BEAT). The desorption of calcium (Ca^{2+}) values from the soil-leachate mixtures across all leachate types (A-E) fall between -0.823 and 3.55. Table 3 reveals intricate desorption patterns for calcium (Ca^{2+}) in the leachate-soil mixtures across various leachate types (A-E) and tested densities ($0 - 2.4 \times 10^9$ cells/ml) within the batch equilibrium adsorption test (BEAT). Unlike the previous observations for potassium (K^+) and sodium (Na^+), the leachate suspension density seems to have a more significant influence on desorption in some cases. Leachate A exhibits a general trend of desorption with decreasing Ca^{2+} concentration (positive values decrease) compared to the initial state (0) at most densities. However, there is a slight increase at the highest density (2.4×10^9 cells/ml), suggesting potential re-adsorption at higher leachate concentrations. Leachate B shows a mixed pattern, with significant negative desorption (strong adsorption) at lower densities, followed by a shift towards desorption (positive values) at higher densities. This suggests a dependence of desorption behavior on leachate concentration. Leachate C displays a similar pattern to leachate B, with initial negative desorption followed by a shift towards desorption at higher densities. However, the magnitude of desorption appears weaker compared to leachate B. Leachate D exhibits a variable desorption pattern. While some densities show desorption, others show negative desorption or minimal change. There is no clear trend with increasing density. Leachate E shows a mixed pattern, with some densities exhibiting desorption and others negative desorption. The explanation on such trends largely depends on the complex interactions where the observed desorption

patterns for Ca^{2+} likely reflect complex interactions between the soil properties, leachate composition, and BEAT conditions. Factors like the presence of competing cations, specific binding sites for calcium on the soil, and the overall cation exchange capacity (CEC) could be influencing the desorption behavior. Also, influence of leachate density is obvious as the varying desorption patterns with increasing leachate density suggest that the leachate composition might be affecting the availability of binding sites or the competition for these sites by other cations present in the leachate. The adsorption isotherms for Ca^{2+} showed in Table 3, both linear and non-linear in shapes, which are the usual occurrence for cations (Hong, 2016; Hong *et al.*, 2016). The adsorbed and desorbed Ca^{2+} ions were in the ranges 0.774 - 3.355; -2.995 - 2.381; 0.685 - 1.911; -6.773 - 2.845; -0.822 - 2.407 and 0.168 - 2.296 mg/l for MSW/leachates A, B, C, D and E, respectively, when soil was treated with leachate suspension density of 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cell/ml, respectively. Retardation factors values recorded are -131.63, -16.26, 8.50, -10.79, -43.45, and 40.16 for soil when treated with suspension density of 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, respectively. The absorption of Ca^{2+} in soil when treated with leachate suspension density of 2.4×10^9 cells/ml could be due to leachate hydrolysis which produced dissolved ammonium and inorganic carbon, and carbon dioxide (CO_2). The desorption isotherms are both linear and non-linear, respectively, in agreement with the findings that desorption or adsorption isotherms can be linear or non-linear (Hong, 2016; Hong *et al.*, 2016; Shackelford and Daniel, 1991). The dissolved ammonia increased the pH of the specimen thus resulting in the accumulation of insoluble calcium carbonate (CaCO_3) in a calcium rich environment (Cui *et al.*, 2021; Sani *et al.*, 2020; Wani and Mir, 2020). As the population of the microbes increased, it was

presumed that the additional enzyme released into the soil could have been responsible for calcite formation

and bioactivities of the microbes that clogged the micro pore within the soil skeleton.

Table 3: Desorption isotherms for Calcium (Ca^{2+}) of leachate Soil– mixtures during batch equilibrium adsorption test (BEAT) for different leachate

	Leachate suspension density(cells/ml)					
Leachate	0	1.5×10^8	6.0×10^8	1.2×10^9	1.8×10^9	2.4×10^9
Leachate A	3.55	2.381	1.911	2.845	2.407	2.296
Leachate B	0.209	-6.207	-3.961	-3.500	-1.375	-3.214
Leachate C	0.388	0.401	-2.350	-2.861	-1.781	-7.512
Leachate D	3.503	1.248	1.481	0.743	3.920	2.892
Leachate E	0.774	-2.995	0.685	-6.773	-0.823	0.168

Adsorption/desorption of magnesium: Table 4 presents the desorption isotherms for magnesium (Mg^{2+}) in the leachate-soil mixtures tested using the batch equilibrium adsorption test (BEAT) across various leachate types (A-E) and densities (0 - 2.4×10^9 cells/ml). The desorption of magnesium (Mg^{2+}) values from the soil-leachate mixtures across all leachate types (A-E) fall between 0.673 and 0.875. Table 4 presents the desorption isotherms for magnesium (Mg^{2+}) in the leachate-soil mixtures tested using the batch equilibrium adsorption test (BEAT) across various leachate types (A-E) and densities (0 - 2.4×10^9 cells/ml). The results suggest limited desorption of Mg^{2+} across all leachates and densities. All leachate types (A-E) show minimal change or slight positive values in Mg^{2+} concentration compared to the initial state (0) at all tested densities. These values are relatively close to each other, suggesting minimal desorption regardless of the leachate type or density. Strong adsorption is the possible explanation in this trend, as the observed limited desorption suggests a strong affinity of the soil for Mg^{2+} . This could be due to the presence of clay minerals with high cation exchange capacity (CEC) or specific binding sites for magnesium. Similarly, BEAT conditions is also another factor, since the BEAT conditions was not favorable for significant Mg^{2+} desorption. Factors like time, pH, or the presence of competing cations could be hindering desorption. Therefore, the adsorption

isotherms for magnesium (Mg^{2+}) shows adsorbed Mg^{2+} ions when soil was treated with leachate suspension density of 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, respectively. These show both linear and non-linear shapes, which is the usual occurrence for cations (Hong and Shackelford, 2017; Hong *et al.*, 2016). The desorption isotherms are linear and non-linear in agreement with the findings that adsorption isotherms can be linear or non-linear (Hong and Shackelford, 2017; Hong *et al.*, 2016). The adsorbed magnesium ion is insignificant and cannot constitute any hazard to the liner system (Osim, 2017). The results obtained are within the limit recorded in the literature (Osim, 2017). The retardation factors (not shown here) for soil treated with leachate suspension density of 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml obtained from laboratory experiments are 53.20, -120.80, -22.84, 146.49, 20.51 and 12.11 respectively. The results show a decrease in the retardation factor which implied reduction in the rate of flow of the chemical contaminant (Mg^{2+} ions) in the soil with increase in leachate suspension density. The retardation factor signifies the comparative rate of fluid flow to the transport rate of a reactive solute (Eberemu *et al.*, 2013). The higher the retardation factor the lower the rate of flow of the chemical contaminant in the soil, as reflected with positive isotherm that suggests the occurrence of adsorption of the ions.

Table 4: Desorption isotherms for Magnesium (Mg^{2+}) of leachate Soil– mixtures during batch equilibrium adsorption test (BEAT) for different leachate

	Leachate suspension density(cells/ml)					
Leachate	0	1.5×10^8	6.0×10^8	1.2×10^9	1.8×10^9	2.4×10^9
Leachate A	0.781	0.840	0.875	0.787	0.763	0.773
Leachate B	0.753	0.793	0.825	0.773	0.7710	0.776
Leachate C	0.673	0.780	0.720	0.700	0.678	0.687
Leachate D	0.681	0.733	0.694	0.683	0.686	0.698
Leachate E	0.710	0.755	0.746	0.706	0.705	0.726

Adsorption/desorption of sulphate: Table 5 displays the desorption isotherms for sulfate (SO_4^{2-}) in the leachate-soil mixtures tested using the batch equilibrium adsorption test (BEAT) across various leachate types (A-E) and densities (0 - 2.4×10^9 cells/ml). Desorption of SO_4^{2-} values from the soil-

leachate mixtures across all leachate types (A-E) fall between 0.201 and 0.463. Table 5 displays the desorption isotherms for sulfate (SO_4^{2-}) in the leachate-soil mixtures tested using the batch equilibrium adsorption test (BEAT) across various leachate types (A-E) and densities (0 - 2.4×10^9

cells/ml). The results suggest limited desorption of SO_4^{2-} across most leachates and densities. All leachate types (A-E) except leachate C show minimal change or slight positive values in SO_4^{2-} concentration compared to the initial state (0) at most tested densities. These values are relatively close to each other, suggesting minimal desorption regardless of the leachate type or density (except leachate C). Leachate C exhibits a desorption trend with decreasing SO_4^{2-} concentration (positive values decrease) at some densities (0, 1.2×10^9 , and 2.4×10^9 cells/ml). This suggests a potential release of sulfate from the soil back into the solution under these specific conditions. Low affinity for soil could be responsible for the observed trend, as the observed limited desorption for most leachates suggests a low affinity of the soil for SO_4^{2-} . Sulfate is a negatively charged ion and may not readily interact with the negatively charged clay minerals in the soil. Also, desorption for leachate C could be another factor, since the observed desorption

for leachate C could be due to specific interactions with the leachate composition. The presence of competing anions in other leachates might be hindering SO_4^{2-} desorption. Overall, the results in Table 5 suggest that sulfate (SO_4^{2-}) exhibits limited desorption from the leachate-soil mixtures under the tested BEAT conditions, except for a potential desorption observed with leachate C. The retardation factors (not shown here) of 61.39, -31.63, -40.91, -22.89, -35.53 and -11.71 were recorded for soil treated with leachate suspension density of 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, respectively both show linear and non-linear in shape (Hong and Shackelford, 2017; Hong *et al.*, 2016) reported that adsorption isotherms can be linear or non-linear. The results show a decrease in the retardation factor which implied reduction in the rate of flow of the SO_4^{2-} in the soil with increase in leachate suspension density.

Table 5: Desorption isotherms for Sulphate (SO_4^{2-}) of leachate Soil– mixtures during batch equilibrium adsorption test (BEAT) for different leachate.

	<i>Leachate suspension density(cells/ml)</i>					
Leachate	0	0.15×10^8	6.0×10^8	1.2×10^9	1.8×10^9	2.4×10^9
Leachate A	0.426	0.332	0.316	0.278	0.297	0.303
Leachate B	0.324	0.279	0.284	0.233	0.271	0.324
Leachate C	0.319	0.249	0.228	0.209	0.201	0.313
Leachate D	0.463	0.396	0.380	0.351	0.327	0.420
Leachate E	0.463	0.391	0.369	0.345	0.353	0.436

Adsorption/desorption of chloride: The values in Table 6 seem very high and negative for chloride (Cl^-) desorption isotherms. The desorption of Cl^- values from the soil-leachate mixtures across all leachate types (A-E) fall between -29551.5 and -16438.7. Table 6 presents the desorption isotherms for chloride (Cl^-) in the leachate-soil mixtures tested using the batch equilibrium adsorption test (BEAT) across various leachate types (A-E) and densities (0 - 2.4×10^9 cells/ml). The adsorption isotherms for chlorine (Cl^-) shown in Table 6, desorbed Cl^- ion values were in the ranges -27066, -16793.72, -18923.72, -28841.53, 18213.72 -28131.53, -28841.53- -18213.72, -29551.53 -18213.72 and -19633.72 29551.53 for MSW leachates A, B, C, D and E, respectively, when soil was treated with leachate suspension density of 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cells/ml, respectively. However, the reported values are very high negative numbers, which are unexpected in the context of desorption studies. Desorption typically involves the release of adsorbed ions from the soil back into the solution. Negative values in desorption studies would imply a significant uptake of Cl^- by the soil from the leachate, even after the initial adsorption process. This is unlikely based on the general understanding of chloride behavior in soils. In the case of retardation factors (not shown here), the

obtained value marginally decreased with leachate suspension density. Values recorded are -7.75, -7.95, -7.41, -7.64, -7.74 and -7.68 for soil treated with leachate suspension density of 0, 1.5×10^8 , 6×10^8 , 1.2×10^9 , 1.8×10^9 and 2.4×10^9 cell/ml, respectively, are linear based on the regressed line (Hong and Shackelford, 2017; Hong *et al.*, 2016). The adsorption isotherms are all linear in agreement with the findings that adsorption isotherms can be linear or non-linear (Shackelford and Daniel; 1991). The results obtained show a low Cl^- adsorption capacity of the treated soil which could be due to the increase in the pH of the soil with higher leachate suspension density. This could be the cause of the observed significant decrease in the adsorption percentage. The decrease in adsorption capacity may be attributed to the diminished electrostatic force of attraction between the oppositely charged adsorbate and adsorbent, consequently leading to a reduction in sorption capacity (Scalia *et al.*, 2018; Amer *et al.*, 2010). The higher the retardation factor values, the greater the ability of the treated soil to reduce contaminant flow. It is believed that variations in pH, environmental factors, and leachate concentration may contribute to the reduced effectiveness of the soil mixture in minimizing contaminant flow, posing an environmental risk in the study area.

Table 6: Desorption isotherms for Chloride (Cl⁻) of leachate Soil- mixtures during batch equilibrium adsorption test (BEAT) for different leachate

	<i>Leachate suspension density(cells/ml)</i>					
Leachate	0	0.15×10 ⁸	6.0×10 ⁸	1.2×10 ⁹	1.8×10 ⁹	2.4×10 ⁹
Leachate A	-16793.7	-18923.5	-18213.1	-18213.2	-18213.3	-19633.0
Leachate B	-18568.4	-16438.7	-16758.2	-16083.4	-15373.2	-16438.8
Leachate C	-21914.5	-22269.5	-22617.9	-21559.5	-20849.7	-23334.4
Leachate D	-26150.1	-22600.2	-25043.0	-25795.2	-20825.2	-24020.2
Leachate E	-27066.5	-28841.5	-28131.3	-28841.3	-29551.3	-29551.5

Effect of pH on batch equilibrium adsorption: The results of the effect of pH and electrical conductivity on the leachate behavior on the dumpsite soils of the study areas are presented in Table 7 and 8, respectively. Table 7 shows the pH values of leachate-soil mixtures across various leachate types (A-E) and tested densities (0 - 2.4 x 10⁹ cells/ml) during the batch equilibrium adsorption test (BEAT). The pH values of leachate-soil mixtures across various leachate types (A-E) fall between 8.76 and 10.34. Table 7 shows the pH values of leachate-soil mixtures across various leachate types (A-E) and tested densities (0 - 2.4 x 10⁹ cells/ml) during the batch equilibrium adsorption test (BEAT). The results suggest that the leachate had a limited impact on the overall pH of the mixtures. The pH values range from 8.76 to 10.34, indicating a slightly alkaline to moderately alkaline condition throughout the tests. There are no clear trends in pH with respect to leachate type or suspension density. The pH values for each leachate type show minor variations across the different densities. The explanation might be that the dumpsite soil might have a high buffering capacity, which helps resist changes in pH upon the addition of acidic or basic leachates. This buffering capacity could be due to the presence of clay minerals or carbonates in the soil. Or, it might be that there was limited leachate-soil interaction, as the BEAT test conditions, such as the ratio of leachate to soil or the contact time, might not have been sufficient for the leachate to significantly alter the overall pH of the mixtures. On the other hand, it is important to compare the pH observations in Table 7

with the desorption results from previous tables (Tables 1-6) to see if there are any correlations. For instance, if a specific leachate type caused a significant decrease in pH (more acidic), it might influence desorption behavior of certain cations by affecting the electrostatic interactions between the soil particles and the ions. It was reported that pH is a factor that controls the adsorption of cations during batch equilibrium adsorption test, due to the fact that inter- particle repulsions generally happen in high pH environment, while positive edge charges in low pH environment are present (Abollino *et al.*, 2003). It was observed that pH generally decreased with increase in leachate suspension density up to 2.4 x 10⁹ cells/ml except for a few cases. The recorded decrease in pH values could be due to the fact that adsorption of metals decreases with decreasing pH (Naka *et al.*, 2016; Abollino *et al.*, 2003), while the few recorded increase could be due to desorption of metals ions. Also, chemical reaction between the constituent of the individual leachate, suspensions and the cementation reagent used may also be responsible for the alteration of the pH values of the treated soil. Hydrolysis and biogeochemical processes within the soil – leachate mixtures exposed to MSW leachates may be responsible for the documented behaviors. Overall, the results in Table 7 suggest that the leachate had a limited impact on the pH of the dumpsite soil-mixtures under the tested BEAT conditions. Further investigation is recommended to explore how leachate composition, pH, and contact time influence desorption behavior and contaminant mobility within landfills.

Table 7: Tests results for pH of dumpsite soil – mixtures during batch equilibrium adsorption test (BEAT) for different leachate.

	<i>Leachate suspension density(cells/ml)</i>					
Leachate	0	0.15×10 ⁸	6.0×10 ⁸	1.2×10 ⁹	1.8×10 ⁹	2.4×10 ⁹
Leachate A	9.83	10.3	10.34	9.96	9.95	10.05
Leachate B	8.76	9.87	9.92	9.72	9.58	9.76
Leachate C	10.17	10.17	10.21	10.2	9.96	9.90
Leachate D	10.15	10.17	9.99	9.93	9.9	9.84
Leachate E	10.07	10.17	10.01	9.62	9.69	9.70

Effect of electrical conductivity on batch equilibrium adsorption: Table 8 shows the electrical conductivity (EC) of leachate-soil mixtures across various leachate types (A-E) and tested densities (0 - 2.4 x 10⁹ cells/ml) during the batch equilibrium adsorption test (BEAT). The electrical conductivity (EC) of leachate-soil mixtures across various leachate types (A-E) fall

between 1.3 and 25. Table 8 shows the electrical conductivity (EC) of leachate-soil mixtures across various leachate types (A-E) and tested densities (0 - 2.4 x 10⁹ cells/ml) during the batch equilibrium adsorption test (BEAT). The results reveal inconsistent patterns in EC across leachate types and densities. There is no clear trend in EC with respect to

leachate type. Some leachates (A and D) show a decrease in EC upon mixing with the soil, while others (C) show an increase, and leachate E exhibits a large decrease at the highest density only. The impact of leachate suspension density on EC is also inconsistent. Some leachates (A and B) show a slight decrease in EC with increasing density, while others (C and D) show no clear trend. Notably, leachate E displays a significant increase in EC at the highest density (2.4×10^9 cells/ml). The possible explanation might be due to dilution by deionized water, since the BEAT test involved use of deionized water for preparing the mixtures. The initial high EC of the leachate might be diluted upon mixing with the soil and deionized water, leading to a decrease in EC observed for some leachates (A and D). Also, it might be that dissolution of soluble salts could responsible of the observed trend, as in some cases (leachate C), the interaction between the leachate and the soil might lead to the dissolution of soluble salts present in the soil, resulting in an increase in EC. In addition, the varying responses in EC across leachate types could be due to differences in the ionic composition of the leachates and the properties of the dumpsite soil. The specific types of ions present and their interaction with the soil particles

might influence the overall EC of the mixtures. The significant increase in EC for leachate E at the highest density is unexpected and requires further investigation. It is possible that there might be an error in the measurement or an unusual interaction between this specific leachate and the soil at high density. In the same vein, it was reported that EC is related to the increase in the degree of salinity of the solution formed from the reaction of leachate with soil (Naka *et al.*, 2016). This ionic presence alters some properties of the soil and the activities of micro-organisms in the soil (Naveen *et al.*, 2018; Naka *et al.*, 2016; Ghosh *et al.*, 2013). The variation of electrical conductivity (EC) of soil with leachate suspension density for the various MSW leachates considered is shown in Table 8. The EC values of soil generally increased marginally with stepped increase in leachate suspension density when exposed to MSW leachates A, B, C, D, E and F respectively. Overall, the results in Table 8 show inconsistent patterns in electrical conductivity of the leachate-soil mixtures during the BEAT test. Further investigation is needed to elucidate the factors influencing EC, including leachate composition, soil properties, and potential interactions between them.

Table 8: Tests results for Electrical conductivity of dumpsite soil – mixtures during batch equilibrium adsorption test (BEAT) for different leachate.

Leachate	Leachate suspension density(cells/ml)					
	0	0.15×10^8	6.0×10^8	1.2×10^9	1.8×10^9	2.4×10^9
Leachate A	16	1.4	1.4	1.4	18	18
Leachate B	5.6	1.5	1.4	1.4	1.3	13.6
Leachate C	14	1.3	21	21	22	22
Leachate D	18	1.5	22	22	21	23
Leachate E	14.6	1.4	24	25	25	3

Consequences of leachate on void ratio: Similarly, the results of the impacts of leachate on void ratio, porosity, degree of saturation, and dry density of dumpsite soils are presented in Table 9-12, respectively. Table 9 presents the consequences of leachate on the void ratio of soil-mixtures under different permeation methods (water only, sequential water-leachate, leachate only) and leachate suspension densities ($0 - 2.4 \times 10^9$ cells/ml). The void ratio for "water only" permeation shows a decrease from 0.550 to 0.400 with increasing density. Table 9 presents the consequences of leachate on the void ratio of soil-mixtures under different permeation methods (water only, sequential water-leachate, leachate only) and leachate suspension densities ($0 - 2.4 \times 10^9$ cells/ml). The results suggest that leachate can influence the void ratio, potentially impacting the long-term hydraulic conductivity of the soil mixture. Water permeation represents the void ratio for "water only" where permeation shows a decrease from 0.550 to 0.400 with increasing density, indicating soil compaction. On the leachate impact, compared to water only, both

"sequential water-leachate" and "leachate only" permeation methods resulted in higher void ratios across most densities. This suggests that leachate might be causing some disaggregation or rearrangement of soil particles, leading to an increase in void space. This might be explained that leachate might contain components that dissolve cementing agents or organic matter in the soil, leading to a looser packing of soil particles and an increase in void ratio. On the other hand, leachate could also have a clogging effect on some soil pores at higher densities, potentially reducing the void ratio. The observed increase in void ratio for most cases suggests disaggregation might be the dominant process under these test conditions. The recorded decrease in void ratio could be due to calcite formed which blocked the micro pores within the soil matrix (Li Chi *et al.*, 2018; Choi *et al.*, 2016). It was observed that a general trend of decrease in the final porosity values with increase in leachate suspension density was recorded for the three modes of permeation of specimens considered. The decrease in porosity, which is directly related to

the void ratio, was due to the reduction in volume of voids within the soil skeleton as discussed above. Thus, on hydraulic conductivity implications, changes in void ratio can significantly impact hydraulic conductivity. An increase in void ratio generally corresponds to an increase in hydraulic conductivity, which could affect the rate of contaminant transport

within the landfill. Overall, the results in Table 9 suggest that leachate can influence the void ratio of soil-mixtures, potentially increasing it and impacting the long-term hydraulic conductivity. However, further investigation is recommended to elucidate the specific mechanisms involved and their consequences for contaminant transport within landfills.

Table 9: Consequences of leachate on void ratio for long-term hydraulic conductivity soil–mixture.

Permeation method	Leachate suspension density(cells/ml)					
	0	1.5×10^8	6.0×10^8	1.2×10^9	1.8×10^9	2.4×10^9
Water only	0.550	0.479	0.470	0.470	0.400	0.471
Sequential with water and leachate	0.784	0.479	0.477	0.456	0.506	0.50
Leachate only	0.481	0.470	0.500	0.487	0.481	0.485

Consequences of leachate on porosity: Table 10 presents the consequences of leachate on the porosity of soil-mixtures under different permeation methods (water only, sequential water-leachate, leachate only) and leachate suspension densities ($0 - 2.4 \times 10^9$ cells/ml). The porosity for "water only" permeation shows a decrease from 0.355 to 0.286 with increasing density. Table 10 presents the consequences of leachate on the porosity of soil-mixtures under different permeation methods (water only, sequential water-leachate, leachate only) and leachate suspension densities ($0 - 2.4 \times 10^9$ cells/ml). Similar to the void ratio observations in Table 9, the results suggest that leachate can influence porosity, potentially impacting the long-term hydraulic conductivity of the soil mixture. The porosity for "water only" permeation shows a decrease from 0.355 to 0.286 with increasing density, indicating a decrease in pore space due to soil compaction. On the leachate impact, compared to water only, both "sequential water-leachate" and "leachate only" permeation methods resulted in higher porosities across most densities. This is consistent with the void ratio observations and suggests that

leachate might be causing some disaggregation or rearrangement of soil particles, leading to an increase in pore space. On the connection to void ratio and hydraulic conductivity. Porosity is directly related to void ratio. An increase in porosity observed here corresponds to the increase in void ratio from Table 9. As mentioned previously, changes in void ratio and porosity can significantly impact hydraulic conductivity. An increase in these parameters generally corresponds to an increase in hydraulic conductivity, which could affect the rate of contaminant transport within the dumpsites. Overall, the results in Table 10 suggest that leachate can influence the porosity of soil-mixtures, potentially increasing it and impacting the long-term hydraulic conductivity. However, it is important to note that, in the fields of science and engineering, hydraulic conductivity is a fundamental property of porous materials, soils, and rocks. It characterizes the relative ease with which a fluid can permeate through the pore space or fracture network within the soil or rock compartments.

Table 10: Consequences of leachate on porosity for long-term hydraulic conductivity soil–mixtures.

Permeation method	Leachate suspension density(cells/ml)					
	0	1.5×10^8	6.0×10^8	1.2×10^9	1.8×10^9	2.4×10^9
Water only	0.355	0.324	0.320	0.320	0.286	0.320
Sequential with water and leachate	0.439	0.324	0.323	0.313	0.336	0.334
Leachate only	0.325	0.320	0.333	0.328	0.325	0.327

Consequences of leachate on degree of saturation: Table 11 displays the consequences of leachate on the degree of saturation of soil-mixtures under different permeation methods (water only, sequential water-leachate, leachate only) and leachate suspension densities ($0 - 2.4 \times 10^9$ cells/ml). The degree of saturation for "water only" permeation is generally high (>85%), reaching 100% at some densities. Table 11 displays the consequences of leachate on the degree of saturation of soil-mixtures under different

permeation methods (water only, sequential water-leachate, leachate only) and leachate suspension densities ($0 - 2.4 \times 10^9$ cells/ml). The degree of saturation is a crucial factor influencing hydraulic conductivity. The degree of saturation for "water only" permeation is generally high (>85%), reaching 100% at some densities. This indicates that the soil pores are mostly filled with water. On the impact of leachate impact, compared to water only, the degree of saturation shows a more mixed response with leachate

exposure. "Sequential water-leachate" exhibits a decrease in saturation at lower densities but reaches 100% at higher densities similar to water only. "Leachate only" shows saturation values closer to water only at some densities but also has lower saturation values at other densities. On the hydraulic conductivity implications, hydraulic conductivity is generally higher for saturated soils (degree of saturation closer to 100%) compared to unsaturated soils. The results suggest that leachate exposure might not significantly alter the degree of saturation in some cases ("leachate only" at higher densities), potentially leading to minimal impact on hydraulic conductivity. However, the decrease in saturation observed for "sequential water-leachate" at lower densities and "leachate only" at some densities could indicate a potential decrease in hydraulic conductivity for these scenarios. The observed increase in the degree of saturation is correlated with a rise in the formation of CaCO₃ crystals within the dumpsite soil as a result of increased leachate suspension density. This suggests that alterations in the degree of saturation have an impact on both calcite precipitation and the hydraulic conductivity of treated soil. Research conducted on the cementation of sand at varying degrees of saturation revealed that specimens tested at 20% saturation

displayed a lower presence of CaCO₃ crystals, constituting less than half of those precipitated at 100% saturation (Cheng *et al.*, 2013). Furthermore, the study encompassed an examination of diverse geochemical processes, bioactivity, and interactions between soil and leachate. However, to understand the interplay between leachate composition, void ratio/porosity changes (from Tables 9 and 10), and degree of saturation, it would be helpful to analyze the hydraulic conductivity of the soil mixtures after leachate permeation. This would provide a more complete picture of how leachate exposure might be influencing the flow properties of the dumpsites material. In addition, investigating the mechanisms behind the observed changes in saturation, such as potential air entrapment or pore clogging by leachate components, could provide valuable insights. Overall, the results in Table 11 suggest that leachate can have a mixed impact on the degree of saturation of soil-mixtures. While some cases might not show significant changes, others might indicate a potential decrease in saturation and hydraulic conductivity. However, further investigation is recommended to elucidate the interplay between leachate properties, void ratio/porosity changes, and their combined effects on the flow behavior within dumpsites.

Table 11: Consequences of leachate on degree of saturation for long-term hydraulic conductivity soil– mixtures.

Permeation method	Leachate suspension density(cells/ml)					
	0	0.15×10^8	6.0×10^8	1.2×10^9	1.8×10^9	2.4×10^9
Water only	85.17	92.18	100.00	96.73	98.36	100.00
Sequential with water and leachate	58.47	93.69	100.00	96.00	97.52	98.01
Leachate only	92.73	94.38	100.00	92.41	92.95	100.00

Consequences of leachate on dry density: Table 12 presents the consequences of leachate on the dry density of soil-mixtures under different permeation methods (water only, sequential water-leachate, leachate only) and leachate suspension densities (0 - 2.4×10^9 cells/ml). The dry density for "water only" permeation shows a slight increase with increasing density. Table 12 presents the consequences of leachate on the dry density of soil-mixtures under different permeation methods (water only, sequential water-leachate, leachate only) and leachate suspension densities (0 - 2.4×10^9 cells/ml). Dry density values varied in the ranges 1.69 - 1.78 Mg/m³ for specimens permeated with water only, 1.69 - 1.74 Mg/m³ for specimens sequentially permeated with water and leachate as well as 1.77 - 1.76 Mg/m³ for specimens permeated with leachate only. Dry density is an important parameter for characterizing soil compaction and can indirectly influence hydraulic conductivity. The dry density for "water only" permeation shows a slight increase with increasing density, which is an expected trend due to soil

compaction during the preparation of the mixtures. There was a minimal leachate effect, as compared to water only, both "sequential water-leachate" and "leachate only" permeation methods show minimal to no significant changes in dry density across most densities. On the hydraulic conductivity considerations, dry density is inversely related to void ratio and porosity (discussed in Tables 9 and 10). An increase in dry density indicates a decrease in void space. While the dry density changes are minimal here, the previously observed increases in void ratio and porosity with leachate exposure suggest that leachate might be counteracting the compaction process to some extent. On the other hand, the increase in dry density could be associated with an increase in the stiffness of the soil due to the rise in leachate suspension density. With the increased leachate, it is presumed that calcite precipitation, bio-clogging, microbial activities, and biogeochemical processes also increased. This led to a reduction in the voids within the soil structure, causing the soil particles to bind together, thereby increasing the mass of soil per

unit volume (Wani and Mir, 2021; Ahenkorah, *et al.*, 2020; Putra *et al.*, 2020).

Table 12: Consequences of Leachate on dry density for long-term hydraulic conductivity soil–mixtures.

Permeation method	Leachate suspension density(cells/ml)					
	0	0.15×10^8	6.0×10^8	1.2×10^9	1.8×10^9	2.4×10^9
Water only	1.69	1.77	1.78	1.79	1.78	1.87
Sequential with water and leachate	1.67	1.77	1.80	1.77	1.75	1.74
Leachate only	1.77	1.78	1.76	1.75	1.76	1.77

Conclusions: This study investigated the interplay between leachate adsorption/desorption dynamics and their influence on dumpsites' soil properties and associated environmental risks. While the research focused on common leachate cations (K^+ , Na^+ , Ca^{2+} , Mg^{2+}) and anions (SO_4^{2-} , Cl^-), the impact on key geotechnical properties like void ratio, porosity, degree of saturation, and dry density was likely minimal. However, the study revealed that the dumpsites' soil samples exhibited low affinity or adsorption coupled with a high desorption rate for these specific ions. This finding highlights a significant environmental concern, as it increases the mobility of these ions within the dumpsites, potentially leading to contamination of surrounding soil and water resources. Understanding these dynamics can inform strategies for mitigating environmental risks associated with leachate migration. Implementing leachate treatment processes, selecting low-permeability liners, and choosing cover materials with higher adsorption capacities for these specific ions are crucial approaches for minimizing contaminant movement. Additionally, ongoing monitoring and remediation efforts are essential for long-term environmental protection. Hence, the observed changes in soil properties due to leachate adsorption emphasize the importance of designing landfills with a high capacity for ion adsorption. This can help mitigate potential environmental issues and contribute to a more balanced ecosystem.

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REFERENCES

Abollino, O; Aceto, M; Malandrino, M; Sarzanini, C; Mentasti, E (2003). Adsorption of Heavy Metals on Na-montmorillonite. Effect of pH and Organic

Substances. *Wat. Res.* 37(7): 1619-1627. [https://doi.org/10.1016/S0043-1354\(02\)00524-9](https://doi.org/10.1016/S0043-1354(02)00524-9)

Adamu, H (2021). Photocatalytic remediation of nitrate in aqueous environment by TiO_2 -based photocatalysts– influence of organic hole scavenger on the selectivity of reaction. In *Online International Conference on Catalysis and Chemical Engineering* (pp. 04-05).

Adamu, H; Dubey, P; Anderson, JA (2016). Probing the Role of Thermally Reduced Graphene Oxide in Enhancing Performance of TiO_2 in Photocatalytic Phenol Removal from Aqueous Environments. *Chem. Eng. J.* 284: 80-388. DOI: doi.org/10.1016/j.cej.2015.08.147

Adamu, H; McCue, AJ; Taylor, RS; Manyar, HG; Anderson, JA (2017). Simultaneous Photocatalytic Removal of Nitrate and Oxalic Acid over Cu_2O/TiO_2 and Cu_2O/TiO_2 -AC Composites. *Appl. Catal. B: Environ.* 217: 181-191. DOI: doi.org/10.1016/j.apcatb.2017.05.091

Adamu, H; McCue, AJ; Taylor, RS; Manyar, HG; Anderson, JA (2019). Influence of Pretreatment on Surface Interaction between Cu and Anatase- TiO_2 in the Simultaneous Photoremediation of Nitrate and Oxalic Acid. *J. Environ. Chem. Eng.* 7(2): 103029. DOI: doi.org/10.1007/s11356-018-3120-x

Adamu, H; Shand, M; Taylor, RS; Manyar, HG; Anderson, JA (2018). Use of Carbon-based Composites to Enhance Performance of TiO_2 for the Simultaneous Removal of Nitrates and Organics from Aqueous Environments. *Environ. Sci. Pollut. Res.* 25:32001-32014. DOI: doi.org/10.1007/s11356-018-3120-x

Adamu, H; Anderson, JA (2015). Insights into Competitive Adsorption Between Nitrate and Oxalic Acid over TiO_2 and Consequences for Photocatalytic Remediation. In *Proceedings of the*

- World Congress on New Technologies (NewTech 2015), Barcelona, Spain (pp. 15-17).
Build. Mater. 120: 623-629.
<https://doi.org/10.1016/j.conbuildmat.2016.05.124>
- Adar, E; Bilgili, MS (2015). The Performance of Four Different Mineral Liners on the Transportation of Chlorinated Phenolic Compounds to Groundwater in Landfills. *The Sci. World J.* 2015(1): 171284.
<https://doi.org/10.1155/2015/171284>
- Ahenkorah, I; Rahman, MM; Karim, MR; Teasdale, PR (2020). A Comparison of Mechanical Responses for Microbial-and Enzyme-induced Cemented Sand. *Géotechnique Lett.* 10(4): 559-567. <https://doi.org/10.1680/jgele.20.00061>
- Ahmed, R; Yamin, T; Ansari, MS; Hasany, SM (2006). Sorption Behaviour of Lead (II) Ions from Aqueous Solution onto Haro River Sand. *Adsorp. Sci. Technol.* 24(6): 475-486.
<https://doi.org/10.1260/026361706780154>
- Aloko, DF; Auta, M (2006). Model Development of the Adsorption of Some Cations on Manganese Dioxide (MnO₂) Used in A Lechlanche Dry Cell. *Leonardo J. Sci.* 8: 13–20.
<http://repository.futminna.edu.ng:8080/jspui/handle/123456789/15185>
- Amer, MA; Khaili, FI; Awwad, AM (2010). Adsorption of Lead, Zinc and Cadmium Ions on Polyphosphate-Modified Kaolinite Clay. *J. Environ. Chem. Ecotoxicol.* 2(1): 1–8.
<http://www.academicjournals.org/jece>
- Babakura, B; Adamu, H; Yuguda, AU; Tafida, UI; Akanang, H; Muhammad, KY; Sabo, A (2023). Adsorptive Removal of Chromium from Tannery Wastewater by Chitosan Modified-Activated Carbon of Hyphaene Thebaica. *Sci. Forum J. Pure Appl. Sci.* 23: 191-214.
- Boateng, TK; Opoku, F; Akoto, O (2019). Heavy Metal Contamination Assessment of Groundwater Quality: A Case Study of Oti Landfill Site, Kumasi. *Appl. Wat. Sci.* 9(2): 33.
<https://doi.org/10.1007/s13201-019-0915-y>
- Cheng, L; Cord-Ruwisch, R; Shahin, MA (2013). Cementation of Sand Soil by Microbially Induced Calcite Precipitation at Various Degrees of Saturation. *Canadian Geotech. J.* 50(1): 81-90.
<https://doi.org/10.1139/cgj-2012-0023>
- Choi, SG; Wang, K; Chu, J (2016). Properties of Biocemented, Fiber Reinforced Sand. *Constr.*
- Cui, MJ; Zheng, JJ; Chu, J; Wu, CC; Lai, HJ (2021). Bio-mediated Calcium Carbonate Precipitation and its Effect on the Shear Behaviour of Calcareous Sand. *Acta Geotechnica.* 16: 1377-1389.
<https://doi.org/10.1007/s11440-020-01099-0>
- Dejong, JT; Soga, K; Kavazanjian, E; Burns, S; Van Paassen, LA; Al Qabany, A; Weaver, T (2014). Biogeochemical Processes and Geotechnical Applications: Progress, Opportunities and Challenges. In *Bio-and chemo-mechanical processes in geotechnical engineering: géotechnique symposium in print 2013* (pp. 143-157). Ice Publishing.
- DeJong, JT; Mortensen, BM; Martinez, BC; Nelson, DC (2010). Bio-mediated Soil Improvement. *Ecol. Eng.* 36(2): 197-210.
<https://doi.org/10.1016/j.ecoleng.2008.12.029>
- Eberemu, AO; Kundiri, AM; Shettima, MI; Muhammed, AS (2017) The Remediation Potential of Ordinary Portland Cement(OPC) Admixed with Millet Husk Ash on a Scrap Metal Dump Site Contaminated Soil. *Proceedings of the 2nd Symposium on Coupled Phenomena in Environmental Geotechnics (CPEG2)*, Leeds, United Kingdom, 6 – 8 September. Session: Clean-ups, Paper #64, Pp. 1 – 6.
- Eberemu, AO; Amadi, AA; Edeh, EJ (2013). Diffusion of Municipal Waste Contaminants in Compacted Lateritic Soil Treated with Bagasse Ash. *J. Environ. Earth Sci.* 70:789-797.
<https://doi.org/10.1007/s12665-012-2168-z>
- Francisca, FM; Glatstein, DA (2010). Long Term Hydraulic Conductivity of Compacted Soils Permeated with Landfill Leachate. *Appl. Clay Sci.* 49(3): 187-193.
<https://doi.org/10.1016/j.clay.2010.05.003>
- Ghosh, S; Mukherjee, S; Al-Hamdan, AZ; Reddy, KR (2013). Efficacy of Fine-grained Soil as Landfill Liner Material for Containment of Chrome Tannery Sludge. *Geotech. Geol. Eng.* 31: 493-500.
<https://doi.org/10.1007/s10706-012-9601-7>
- Hong, CS; Shackelford, CD (2017). Characterizing Zeolite-amended Soil-bentonite Backfill for Enhanced Metals Containment with Vertical Cutoff Walls. In *Geoenviron. Eng.* (pp. 82-98).

- Hong, CS; Shackelford, CD; Malusis, MA (2016). Adsorptive Behavior of Zeolite-amended Backfills for Enhanced Metals Containment. *J. Geotech. Geoenviron. Eng.* 142(7): 04016021. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001481](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001481)
- Li Chi, LC; Yao De, YD; Liu ShiHui, LS; Zhou TuanJie, ZT; Bai, S; Gao Yu, GY; Li Lin, LL (2018). Improvement of Geomechanical Properties of Bio-remediated Aeolian Sand. *Geomicrobiol. J.* 3: 2918. <https://www.tandfonline.com/doi/full/10.1080/01490451.2017.1338798>
- McGechan, MB; Lewis, DR (2002). SW—soil and Water: Transport of Particulate and Colloid-sorbed Contaminants through Soil, part 1: General Principles. *Biosystems Eng.* 83(3): 255-273. <https://doi.org/10.1006/bioe.2002.0125>
- McGregor, R. (1999). “Remediation of A Heavy Metal Plume Using a Reactive Wall”. In *Situ and on Site Bioremediation, The Fifth International Symposium*, Battelle, San Diego, CA, April pp. 19-22.
- Naka, A; Flores, G; Katsumi, T; Sakanakura, H (2016). Factors Influencing Hydraulic Conductivity and Metal Retention Capacity of Geosynthetic Clay Liners Exposed to Acid Rock Drainage. *Japanese Geotech. Soc. Spec. Public.* 2(69): 2379-2384. <https://doi.org/10.3208/jgssp.IGS-43>
- Ng, C; Losso, JN; Marshall, WE; Rao, RM (2002). Freundlich Adsorption Isotherms of Agricultural By-product-based Powdered Activated Carbons in a Geosmin–water System. *Biores. Technol.* 85(2): 131-135. [https://doi.org/10.1016/S0960-8524\(02\)00093-7](https://doi.org/10.1016/S0960-8524(02)00093-7)
- Naveen, BP; Sumalatha, J; Malik, RK (2018). A Study on Contamination of Ground and Surface Water Bodies by Leachate Leakage from A Landfill in Bangalore, India. *Int'l J. Geo-Eng.*, 9(1): 27. <https://doi.org/10.1186/s40703-018-0095-x>
- Okparanma, RN; Ayotamuno, MJ (2008). Predicting Chromium (VI) Adsorption Rate in the Treatment of Liquid-phase Oil-based Drill Cuttings. *Afr. J. Environ Sci. Technol.* 2(4): 068-074.
- Oliver, DP; McLaughlin, MJ; Naidu, R; Smith, LH; Maynard, EJ; Calder, IC (1999). Measuring Pb Bioavailability from Household Dusts Using an *Invitro* Model. *Environ. Sci. Technol.* 33(24): 4434-4439. <https://doi.org/10.1021/es981212n>
- Osim, AR (2017). Compacted Cement Kiln Dust Treated Black Cotton Soil as Suitable Liner and Cover Material in Waste Containment Facilities. *Unpublished Ph. D Thesis. Department of Civil Engineering Ahmadu Bello University Zaria.*
- Osinubi, KJ; Yohanna, P; Eberemu, AO; Ijimdiya, TS (2019). Evaluation of Hydraulic Conductivity of Lateritic Soil Treated with *Bacillus Coagulans* for Use in Waste Containment Applications. In *Proceedings of the 8th International Congress on Environmental Geotechnics Volume 3: Towards a Sustainable Geoenvironment 8th* (pp. 401-409). Springer Singapore.
- Osinubi, KJ; Liman, AS; Moses, G (2014). Batch Equilibrium Analysis of Compacted Cement Kiln Dust Treated Lateritic Soil. In *Geoenvironmental Engineering* (pp. 181-190).
- Osinubi, K; Eberemu, A (2009). Compatibility and Attenuative Properties of Blast Furnace Slag Treated Laterite. *The J. Solid Waste Technol. Manag.* 35(1): 7-16. <https://doi.org/10.5276/JSWTM.2009.7>
- Putra, H; Yasuhara, H; Erizal, A; Sutoyo, B; Fauzan, M (2020). Review of Enzyme-induced Calcite Precipitation as a Ground-improvement Technique. *Infrastruc.* 5(8): 66. <https://doi.org/10.3390/infrastructures5080066>
- Sani, JE; Moses, G; Oriola, FOP (2020). Evaluating the Electrical Resistivity of Microbial-induced Calcite Precipitate-treated Lateritic Soil. *SN Appl. Sci.* 2: 1-12. <https://doi.org/10.1007/s42452-020-03285-x>
- Scalia, J; Bareither, CA; Shackelford, CD (2018). Advancing the Use of Geosynthetic Clay Liners as Barriers. *Geotech. Eng.* 49(4): 100-114.
- Shackelford, CD; Lu, N; Malusis, MA; Sample-Lord, KM (2019). Research Challenges Involving Coupled Flows in Geotechnical Engineering. *Geotechnical Fundamentals for Addressing New World Challenges*, pp. 237-274.
- Shackelford, CD (1994). Waste-soil Interactions that Alter Hydraulic Conductivity. *Hydraulic Conduct. Waste Cont. Transp. Soil.* 1142: 111.

- Shackelford, CD; Daniel, DE (1991). Diffusion in Saturated Soil. I: Background. *J. Geotech. Eng.* 117(3): 67-484. [https://doi.org/10.1061/\(ASCE\)0733-9410\(1991\)117:3\(467](https://doi.org/10.1061/(ASCE)0733-9410(1991)117:3(467)
- Steve, K; Erika, T; Reynold, T; Paul, M (1998). Activated Carbon: A Unit Operations and Processes of Activated Carbon. *Environ. Eng.* 25: 350-749.
- Wani, KS; Mir, BA (2021). An Experimental Study on the Bio-cementation and Bio-clogging Effect of Bacteria in Improving Weak Dredged Soils. *Geotech. Geol. Eng.* 39: 317-334. <https://doi.org/10.1007/s10706-020-01494-0>
- Wani, KS; Mir, BA (2020). Microbial geo-technology in ground improvement techniques: a comprehensive review. *Innov. Infrastruc. Solut.* 5(3): 82. <https://doi.org/10.1007/s41062-020-00335-6>
- Wuave, T; Sabo, A; Ibrahim, D; Adamu, H (2024a). Geotechnical Properties of Soil Beneath Solid Waste Dumpsite: Case Study of Plateau State, Nigeria. *J. Afr. Adv. Sustain. Stud.* 4(2): 17-34.
- Wuave, T; Sabo, A; Ibrahim, D; Adamu, H (2024b). Framework for Developing Engineered Landfill in Jos Plateau State, Nigeria. *J Biodiver. Environ. Res.* <https://ssaapublications.com/sjber/article/view/171>
- Yohanna, P; Eberemu, AO; Osinubi, KJ (2016). Effect of Iron Ore Tailings on some Geotechnical Properties of Cement Stabilized Black Cotton Soil. *Nig. J. Eng.* 22(2): 58-65. <https://doi.org/10.1061/9780784480144.08>