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Environmental and geophysical implications of landfill leachate plumes on groundwater, uppermost topsoil, and engineering foundations

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Abstract: Landfills remain the most widely adopted cost-efficient waste management systems across the globe. However, the infiltration of the landfill leachate plumes emerging from hazardous materials within poorly managed landfill sites remains a significant threat to groundwater resources and civil/environmental engineering foundations, especially in developing nations like Nigeria. To address these concerns, this study assesses the impact of landfill leachate plumes (LLPs) on groundwater, topsoil, and engineering foundations in Kaduna, Nigeria. The objectives of this study include delineating subsurface contamination using geophysical methods, analyzing the physicochemical and heavy metal content of leachate, and evaluating associated environmental and geotechnical risks. Integrated geophysical and laboratory analyses were employed. Electrical Resistivity Tomography (ERT) surveys (5 profiles) and ground magnetic surveys (24 lines) were conducted using an ABEM SAS4000 and an ENVI PRO magnetometer. Data were processed using RES2DINV and Oasis Montaj software. Leachate samples were analyzed via Atomic Absorption Spectrometry to determine heavy metal concentrations (Pb, Cd, Zn, Fe, and Cr), as well as BOD_5, COD, TDS, and EC. ERT results identified severely contaminated zones within the landfill, with resistivity values ranging from 2.8 to 9.0 Ωm compared to 29–150 Ωm off-site areas of depths at 0–3.5 m. Magnetic surveys revealed anomalies from 31095 to 43510 nT, correlating with leachate accumulation at 2–5 m. Hydrochemical analysis showed high heavy metal concentrations (11.17–21.73 mg/L), elevated BOD_5 (809 mg O_2/L) and COD (2104 mg O_2/L), and a BOD_5/COD ratio of 0.385, indicating the presence of biodegradable organic matter. The LLPs contributed significantly to groundwater contamination and the depletion of the supportive topsoil layer. The combined geophysical and hydrochemical methods successfully identified the extent of contamination. The study clearly shows the importance of proper landfill lining, soil treatment, and effective waste management practices in developing countries to safeguard both infrastructural and health conditions. Future study could focus on simulation modeling of contaminant transport.

Introduction

Cities and municipalities are increasingly relying on landfills as the primary means of solid waste disposal due to the sharp increase in waste generation associated with urbanization and industrialization. However, landfill leachate plumes (LLPs) constitute a complex and hazardous liquid waste when they infiltrate the soil (Norouzi, et al., 2022). In the absence of adequate monitoring systems, these plumes can migrate further spread underground, posing serious threats to the environment, including soil, groundwater, and infrastructures, as well as public health systems (Joseph, 2025). The uppermost topsoil layer, which serves as the foundation for engineering structures and overlies groundwater systems, is particularly vulnerable to contamination (Alao, et al., 2023). In many areas where groundwater occurs beneath or adjacent to the topsoil, aquifers, which are the major source of drinkable water, become contaminated through the intrusion of LLPs containing heavy metals and other toxic substances, rendering the water unsuitable for human consumption. Moreover, groundwater remediation is both difficult and costly process once contamination has occurred, thereby exposing populations to prolonged water insecurity and associated health risks.

Leachate interact chemically with soil particles, altering pH levels, increasing porosity and permeability, reducing cohesiveness, and disturbing soil structure. These alterations significantly compromise the soil's mechanical strength and capacity to sustain both surface and subsurface loads (Khodary, et al., 2020; Dangsaraky, et al., 2025). Consequently, engineering foundations and infrastructure such as roads, buildings, and other structures located near landfill sites become highly susceptible to damage (Ezema , et al., 2022). Leachate infiltration can weaken foundation soils, accelerate the corrosion of subsurface materials, and induce uneven settlement, potentially leading to structural deformation or failure. In severe cases, this jeopardizes the safety and functionality of critical infrastructure, necessitating expensive repairs or even complete reconstruction.

The infiltration of landfill leachate into the uppermost topsoil layer accumulates leachate plumes within the topsoil (Ige & Baiyegunhi, 2022; Ibor, et al., 2023), which can pose serious risks to engineering foundations. A remarkable and thorough study carried out in Nigeria showed that the resistivity values of the overburdened topsoil layer, also referred as the engineering layer within the landfill consistently exhibited low electrical resistivity values alternating between 4.1 Ωm and 13.1 Ωm, which was attributed to the presence of a high concentration of heavy metals (HMs) due to the infiltration of the leachate plume. The study noted a series of land cave-ins in the upper layer of the Earth's crust, which resulted in slope and structural failures (Alao, et al., 2023). Furthermore, landfill leachate plumes (LLPs) can result in the degradation of soil structure and fertility. Leachate infiltration can cause compaction and clogging of soil pores, leading to reduced water infiltration and drainage. This can result in waterlogged conditions, affecting root growth and oxygen availability for plants (Norouzi, et al., 2022; Gun et al., 2026; Dai et al., 2026). These effects are consistent with recent evidence that dissolved organic matter, oxygen availability, and redox-active soil–water interfaces can regulate microbial nitrogen cycling, metalloid immobilization, dissolved oxygen dynamics, and reactive oxygen species production in saturated soil–groundwater systems (Zeng et al., 2024; Ge et al., 2026; Alao, et al., 2026). The presence of contaminants in leachate can also disrupt the beneficial microbial communities in the soil (Ojuri, et al., 2018; Parvin & Tareq, 2021), which are essential for nutrient cycling and organic matter decomposition. As a result, the soil's ability to support healthy plant growth and sustain vital ecosystem functions is compromised.

In addition, the plumes migrating into groundwater can further exacerbate the impacts on the overburdened topsoil as the horizontal and vertical movement of the contaminated groundwater through the soil profile can affect the deeper of soil layers (Omali, et al., 2023; Shaji, et al., 2024). The transport of contaminants through the soil can extend the area of impact beyond the immediate vicinity of the landfill, amplifying environmental and agricultural consequences (Golwala, et al., 2022; Islam, et al., 2023). To mitigate the impacts of LLPs on the topsoil, effective remediation strategies and waste management practices are required, including liner systems and leachate collection systems to minimize leachate generation. The impacts of LLPs on topsoil can lead to soil contamination, degradation of soil structure and fertility, and potential groundwater pollution (Grisey & Aleya, 2016). It is imperative to implement proper waste management practices and remediation measures to minimize the release and spread of leachate contaminants, safeguard the integrity of the topsoil, and preserve the quality of the environment. However, there was no concrete law in Nigeria in line with the international regulations that prohibit open dumpsites and uncontrolled landfills (Ojuri, et al., 2018), therefore, a large percentage of waste generations are being emptied in uncontrolled landfills and open dumpsites without adequate soil and water contamination control. Consequently, this study explores the influence of leachate plumes on the natural geophysical signature of the study area using the ERT technique and by implication, the consequence of an overburdened topsoil engineering layer. This was done through comparative assessment by (i) delineating the subsurface geo-electric parameters of the overburdened topsoil overlying the groundwater systems, (ii) determining the resistivity values alongside the depth of the delineated layers (iii) mapping the fault zones as the leachate plumes accumulated regions, (iv) determine whether or not the leachate plumes have contaminated surface layers to assess the regional groundwater quality, and (v) apply i-iv to identify the extend and degree impact of the landfill solid waste on the regional groundwater quality.

Site Description

The landfill under investigation is situated within the Kaduna metropolitan area and spans the geographic coordinates of latitude 10° 30' 40.45" N and and longitude 07° 25' 17.04" E, respectively (Fig 1). The landfill is a non-engineered site with a wide variety of waste items disposed there, including hazardous, industrial, municipal, medical, and household wastes. Nonetheless, biodegradable waste makes up more than two-thirds of the debris. The landfill occupies approximately an area of 12,000 m^2 with an estimate volume of 45,600 m^3, and has been used for waste disposal since approximately 23 years. Field observations and site information indicate that the waste body has an estimated thickness of 1.5–5.6 m with an average height of 3.8 m, although this thickness varies laterally across the dump. The near-surface ground materials are dominated by lateritic sandy clay/clayey sand over weathered basement materials, consistent with the regional basement-complex terrain. The inferred groundwater-flow direction is from NW towards SE, based on water-level measurements, topographic gradient, borehole records drainage direction (Alao, 2025). This flow direction was used to interpret the likely migration pathway of the leachate plume from the landfill body toward the surrounding shallow subsurface and groundwater system.

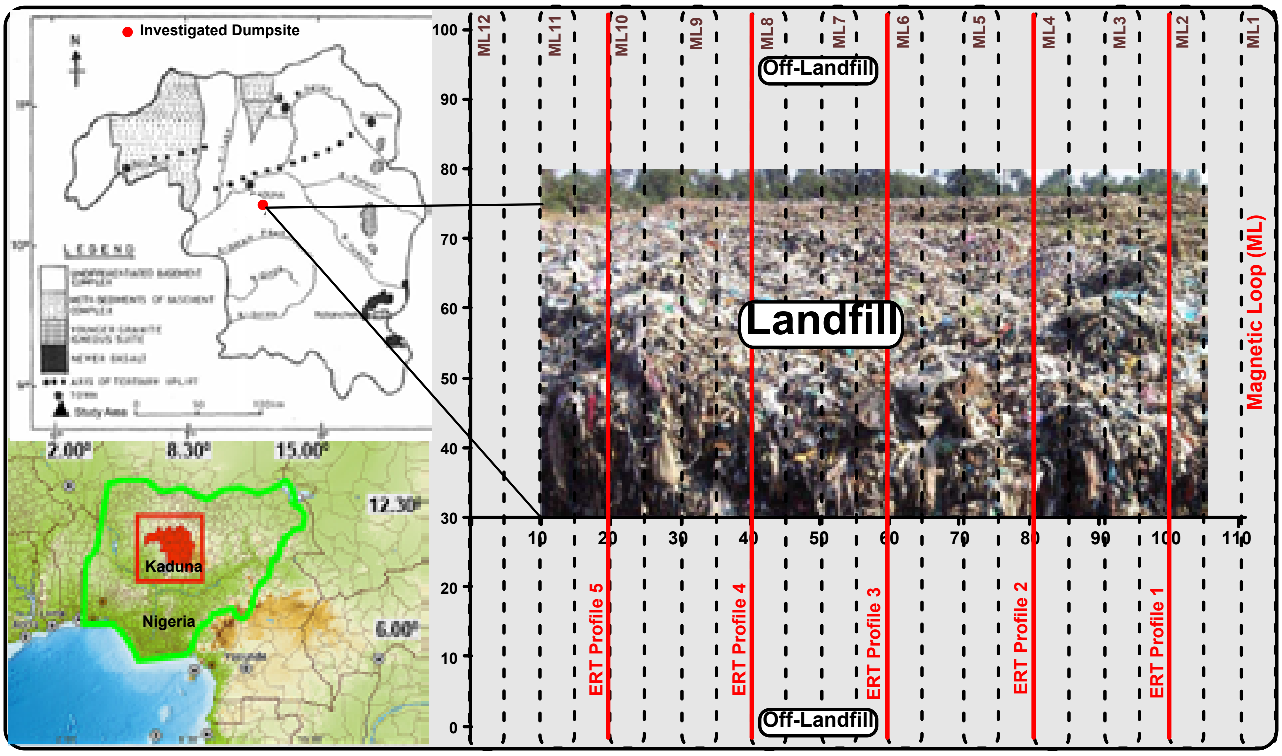

Fig. 1. Description of the study area showing the investigated landfills, ERT, and magnetic profile lines

The characteristics of LLPs are influenced by several regional factors, including hydrology, climate, geology, and the age of the landfill. These parameters may vary from country to country, depending on the location of the landfill (Joseph, et al. 2026). Therefore, the spatio-temporal behaviour of landfill leachate should be interpreted in relation to regional hydrology, water-level dynamics, hydraulic migration pathways, and seasonal environmental forcing in saturated porous media (Feng et al., 2025; Huang et al., 2026; Cheng et al., 2026a; Cheng et al., 2026b). The research area is part of Nigeria's Basement complex, which includes rocks, such as quartz, migmatites, gneisses, schist, and biotite, among other types. However, several intense processes have transformed these crystalline basement rocks into folded and fractured rocks (Abdullahi, et al., 2010). Apart from bed jointing and fractures, the rocks by the district are frequently covered in a mixture of silty, quartzite, sandstone, and laterite soil (Oyawoye, 1970). The laterites eventually developed into lateritic nodules, in contrast to the silty and ammophilous clay soil (Isaac, et al., 2010). Research reveals a structural similarity between the Nigerian Basement Complex and the West African Basement cpmplex (Oyawoye, 1970).

Methodology

Geophysics plays a crucial role in understanding and exploring the Earth's subsurface. However, there are several geophysical methods for investigating natural environmental hazards that provide valuable insights into Earth's dynamics. Two geophysical methods (electrical resistivity and magnetomentry) were employed in this study alongside a laboratory physicochemical analysis technique. The main materials used for this study include but are not limited to an ABEM SAS4000 resistivity meter, an electrode selector, a magnetometer, a 12V battery, electrodes, cables, field hammers, range poles, an atomic absorption spectrometry (AAS) unit, a computer, flasks, beakers, differential pulse anodic stripping voltammetry (DPASV), a global positioning system (GPS), clean plastic bottles (0.75-litre), a shovel, and hoes.

Electrical Resistivity Data Acquisition

A total of five profiles were acquired across the landfill using electrical resistivity imaging (ERI). The survey profiles extended a minimum of 20 m beyond the landfill to serve as a controlled stations for the investigation alongside those previous studies. The data were subsequently processed to generate apparent resistivity field data distributed across the site in a pseudo-section format, and analysis was performed to identify resistivity contrast associated with leachate-accumulated zones as a tool for quantitative analysis. The geo-electrical resistivity method works on the principle of Ohm's law, defined by equation (1):

$$\Delta V = IR \quad (1)$$

However, the electrical resistivity meter measures the subsurface resistance directly, which was transformed into "apparent resistivity (ρ_a) by equation (2), depending on the arrangement of the electrodes, known as the geometry (K) factor. This is because natural seasonal fluctuations affect the electrical resistivity/conductivity of the soil due to water content (Omeiza, et al., 2022; 2023; Joseph, et al. 2024). Thus, the measured resistivity measured is apparent resistivity (ρ_a), which can be defined by equation (2) (Loke, 2000):

$$\rho_a = K\frac{\Delta V}{I} = RK \quad (2)$$

Where K is a geometry factor. For instance, greater depth penetration required wide electrode spacing, which implies that the value of apparent resistivity is electrode-spacing-dependent. For Wenner alpha configuration, the K-factor can be defined by equation (3) (Fig 2):

$$K = 2\pi\left[\left(\frac{1}{a}-\frac{1}{2a}\right)-\left(\frac{1}{2a}-\frac{1}{a}\right)\right]^{-1} \quad (3)$$

Where, (), Thus equation (4) can be simplifiedto equation (4):

$$K = 2a\pi \quad (4)$$

Equation (4) is used to calculate the geometric factor (K-factor) for the Wenner alpha configuration. The materials used and the parameters used for field data acquisition are presented in Table 1.

Magnetic Data Acquisition and Processing

The ground magnetic survey was deployed to measure the total magnetic field (TMF) at the site at regular intervals (5-m grid spacing) along the gridded survey lines using a ground magnetometer (ENVI PRO magnetometer). Each profile contained 21 data points, and with 24 profile, a total of 504 data points were acquired as shown in Fig. 1.The field magnetic data was entered into an automatic contouring computer program (Oasis Montaj), which reveals the magnetic anomalies mapped as leachate accumulated zones (Fig 5). The ground magnetometer works on the force F between two magnetic poles with strengths of m_1 and m_2, separated by the distance (r), as specified by equation (5) (Telford, et al., 1990; Lowrie, 2007):

$$F = \frac{\mu_0 m_1 m_2}{4\pi\mu_R r^2} \quad (5)$$

Where m_1 and m_2 are the strengths of the two magnetic monopoles, r is the distance between the two poles, and μ_0 and μ_R are constants corresponding to the magnetic permeability of the free space and the relative magnetic permeability of the medium separating the poles. The magnetic field B at a point due to a pole of strength m at a distance r from the pole is given by equation (6) (Telford, et al., 1990; Kearey, et al., 2002).

$$B = \frac{\mu_0 m}{4\pi\mu h r^2} \quad (6)$$

At the atomic level, every material, including subsurface rocks, is magnetic (Lowrie, 2007). Induced magnetization, also known as magnetic polarization, is the phenomenon by which a material becomes magnetized when it is placed in a magnetic field but loses magnetization when it is taken out of the field. It arises from the orientation of the material's elementary dipoles, which alignparallel to the direction of the external field with opposite polarity. The induced magnetization intensity I is proportional to the external field strength H (I = χH), and it can be defined by equation (7)

$$I = \chi H \quad (7)$$

Where x is the dimensionless proportionality constant for susceptibility for a specific type of magnetic substance. It may assume positive or negative values. Positive values indicate that the induced magnetic field pointsin the same direction as the inducing field, H, whereas negative values indicate that it point in the opposite direction. The primary material property in magnetic surveying is magnetic susceptibility, and the target's spatial distribution must be ascertained. Analyzing the data for magnetic anomalies that may indicate the presence of leachate-contaminated groundwater requires additional estimation using inversion techniques to determine the depth of the leachate plume through adequate interpretation and mapping. There are several techniques can achieve this, including but are not limited to:

Total Magnetic Intensity (TMI) and Residual Maps: the TMI map is a very useful geophysical tool for displaying the total magnetic field intensity at the Earth's surface, while the residual map helps identify areas where the observed data deviates from the modeled or expected data. These maps are valuable for identifying and understanding the underlying geological structures, such as faults, igneous intrusions, mineral deposits, and magnetic anomalies or data errors.

Euler Deconvolution (ED): ED is a useful geophysical technique for estimating the location and depth of magnetic or gravity sources, particurlally in identifying the depth and geometry of subsurface structures, such as mineral deposits or geological boundaries. Using the ED (Euler's homogeneity equation) approach, one may determine the apparent depth of magnetic anomaly source bodies (Salem, et al., 2002). The degree of homogeneity, which links the location of an anomaly to the derivative components and the magnetic field, can be expressed using the structural index (SI) (Abubakar, 2024; Alao, et al., 2024). A key ED parameter, the SI is an integer that varies depending on the type and field of the magnetic source and is related to the potential-field homogeneity. In geophysics and geology, ED is a valid interpretation technique commonly applied to potential field data for locating magnetic sources and estimating depth. It uses a collection of points (x, y, z) and the so-called SI derivatives with respect to x, y, and z to estimate the position and depth of targets of interest. The structural index (SI) quantifies fall-off rate of the field as a function of distance from the source. According to a noteworthy study (Reid, 2007), the ED can be mathematically described by equation (8) as

$$N(B-M) = (x-x_0)\frac{\partial M}{\partial x} + (y-y_0)\frac{\partial M}{\partial x} + \\ +(z-z_0)\frac{\partial M}{\partial x} \quad (8)$$

Where $(x-x_0)$, $(y-y_0)$, and $(z-z_0)$ denote the positions of the magnetic sources whose magnetic intensities are recorded at (x, y, z), and N, B, and M stand for the structural index, magnetic intensity, and magnetic field, respectively. However, the degree of accuracy of ED in determining the location of the magnetic source is determined by the potential field homogeneity, data quality, and SI.

First Vertical Derivative (FVD): FVG is a mathematical operation applied to enhance subtle features and gradients of the geophysical data such as magnetic or gravity data. It is also effective at identifying edges, boundaries, and anomalies in the data, which are important for geological interpretation (Alao, et al., 2024). Since FVD responds more quickly to changes in the subsurface's properties than the magnetic intensity measured, it has been used in numerous studies to enhance the shallowest subsurface magnetic anomaly source bodies (Raimi, et al., 2014; Pal, et al., 2016; Abubakar, 2025). It is an essential tool for emphasizing a near-surface body over a deeper-seated structure. Equation (9) represents the FVD, which is highly effective in identifying the boundaries of anomalous sources (Dentith & Mudge, 2014) when the height difference between upward and downward continuation at comparable locations is normalized.

$$1VD = \frac{\partial M}{\partial Z} \quad (9)$$

Where M is the magnetic field and ∂Z is the vertical (z-direction) derivative. While the analytical signal demonstrates strength in identifying subsurface targets and defining geologic boundaries, the FVD has shown to be effective in enhancing and mapping lineaments of near-surface magnetic anomaly source bodies (Dentith & Mudge, 2014; Pašteka & Kušnirák, 2020).

Analytical Signal Map (ASM): The ASM is a useful geophysical tool enhancing enhance and interpret magnetic data, derived from the TMI to provide a measure of the amplitude and location of magnetic sources. To accurately define the magnetic anomalies caused by buried objects and to show the magnetic field intensity, analytical signal, or AS, is a complex function. Notable research indicates that the magnitude of the analytical signal can be expressed by equation (10):

$$A(x,y) = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2} \quad (10)$$

Where A is an analytical signal function, M is the magnetic field intensity, and the first-order derivatives of the magnetic field in the *x, y,* and *z* directions are represented by the symbols $\frac{\partial M}{\partial x}, \frac{\partial M}{\partial X}, \frac{\partial M}{\partial x}$, respectively.

Leachate Sampling, Preservation, and Laboratory Analysis

Leachate samples were collected from leachate-accumulation points within the landfill during the season. Sampling pointe were selected based on visible leachate seepage, low-lying accumulation zones, and proximity to geophysical anomaly zones. Samples were collected using pre-cleaned 0.75-L polyethylene bottles that were rinsed with the leachate before final collection. Samples intended for heavy-metal analysis was acidified in the field in situ to pH < 2 using ultrapure nitric acid, stored in an ice chest at approximately 4 °C, and transported to the laboratory for Atomic Absorption Spectrometry analysis. Samples intended for EC, TDS, BOD_5, and COD analyses were preserved at 4 °C and analyzed within the appropriate holding time. Field labels, sample codes, and chain-of-custody records were maintained to ensure traceability. Where applicable, duplicate samples and blank controls were used for quality assurance. However, full preservation metadata were not recorded for all parameters; this limitation is acknowledged, and the interpretation has been restricted to the available measured leachate parameters.

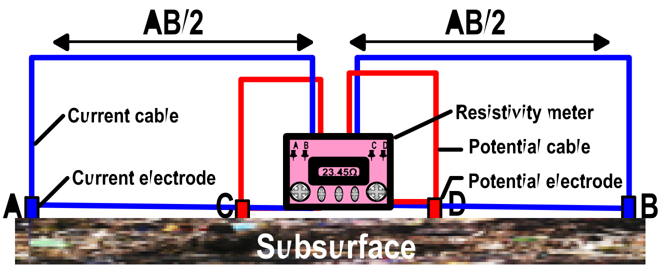

Fig. 2. Wenner Configuration

Result and Discussion

Electrical Resistivity

The results from the ERT investigation show apparent electrical resistivity (AER) within the landfill and average AER away from the landfill (Table 2), which proportionally impact on the regional soil and groundwater. Borehole data around the study area indicate that the overburdened topsoil of the study area is characterized by lateritic, clay, and sandy soil (NWRI, 2011), while the previous studies have revealed that subsurface parameters such as topsoil resistivity and thickness varies between 200 Ωm and 1500 Ωm and 0.5 m and 9.5 m (Kure, et al., 2019). This information provides insighta into the regional geological structure of the study area, enabling adequately interpretation of the current results. The inverse 2D pseudo-sections display pictorial model resistivity traverse profiles shown in Fig 3 and 4. The geo-electrical properties (resistivity and depth) within the landfill and outside the landfill were found to vary between 2.8 Ωm – 9.0 Ωm and 29 Ωm – 150 Ωm, respectively in terms of resistivity values, occurring within the depths 0.0 m – 3.5 m at a horizontal distances of 34.0 m – 65.0 m. This indicate that there is evidence of low resistivity contrasts, delineated as leachate plume accumulation zones

Table 1: Parameters for field data acquisition

SN	Parameter/items	for Electrical Method	Magnetic Method
1	Common materials	field hammer, measuring tape, global position system, field book, etc	
2	Method	Wenner-alpha	Ground-based magnetometer
3	Field equipment or devices	Terrameter ABEM SAS 400, and its accessories	ENVI PRO Magnetometer and its accessories
4	Electrode/data point	48 electrodes	21 · 24 = 504 data points
5	Data station interval	2.50 m electrode Spacing	5.0 m interval
5	Profile	5	24
6	Profile length	100	100
7	Processing software	RES2DINV	Oasis Montaj
8	Survey orientation	North-South	North-South

Table 2: Analysis of geoelectrical parameters across all the profiles showing the horizontal distance and depth of occurrence of suspected landfill leachate plume contaminants.

Profile	Electrical Resistivity Values (Ωm)		Leachate plumes Occurrence		Presumed Implication on Groundwater & Soil
	Off-landfill	Within the landfill	Distance (m)	Depth (m)	
1	47.0 – 150.0	2.8 – 9.0	45.0 – 48.0	0.0 – 3.5	Deeply impacted
2	29.0 – 75.00	3.0 – 8.0	40.0 – 65.0	0.0 – 2.0	Widely impacted
3	34.0 – 100.0	2.8 – 8.0	35.0 – 55.0	0.0 – 2.5	Widely impacted
4	34.0 – 100.0	3.0 – 8.0	38.0 – 65.0	0.0 – 3.5	Deeply & widely impacted.
5	48.0 – 150.0	3.0 – 9.0	34.0 – 50.0	0.0 – 3.2	Deeply impacted

within the landfill across both horizontal (34.0 m – 65.0 m) and vertical (0.0 m – 3.5 m) extents at various depths across the five profiles (Table 2).

Magnetic survey

The magnetic survey design encompassed a grid layout extended beyond the landfill area. A comprehensive ground magnetic survey was conducted at the landfill site to assess the spatial distribution and depth characteristics of leachate plumes using a high-resolution magnetometer. The results of the TMI, residual, first vertical derivative, Euler deconvolution, and analytical signal maps were employed to delineate magnetic anomalies associated with leachate plumes from the magnetic data (Fig 5). Fig 5a presents the investigated site's TMI distributions with values ranging from 31095 nT to 43510 nT and an average of 33,108 nT, which were generated by Oasis Montaj software. Major magnetic anomalies were noted in most of the regions, which may be attributed to the presence of inhomogeneous materials within the landfill. Fig 5b is a magnetic residual map (MRM) of the site, which displays the regional anomaly from the LLPs alongside the landfill materials. Fig 5b also reveals the geologic details of the site. The TMI is correlates with the MRM area of accumulated leachate plume localities. Fig 5c and 5d are enhanced signal maps of the first vertical derivative (FVD) and analytical signal (AS), respectively. Fig 5c demonstrates the distribution of the magnetic anomalies of short-wavelength. The FVD extracted the long wavelength properties of the magnetic field to improve the resolution of the closely spaced and superposed anomalies (Alao, et al., 2024). Subsurface anomalies are observed to occur predominately within the landfill, which are interpretedas magnetic anomalies arising from buried solid waste of magnetic materials. Fig 5d presents the analytical signal map of the site useed to map the subsurface magnetic anomaly body contacts and the edges suspected to the LLPs alongside other magnetic materials within the landfill. According to previous studies, the analytic signal map enhance more subtle magnetic anomalies with a better edge detection of anomalous density around the buried solid waste materials. The magnetic anomalies from the site's materials have a gradient of at least 1248 nT/m. The Euler deconvolution map (EDM), which indicates the depth of occurrence of leachate plume accumulation was overlain on the TMI, MRM, FVD, and AS maps presented in Figs 5-8. Thus, each of the maps was superimposed with EDM to visualize the depth distribution of the leachate plume occurrence.

Fig 5: The magnetic anomalies associated with LLPs within the site: (a) total magnetic intensity measurement, (b) residual map, (c) first vertical derivative map, and (d) analytical signal map

Hydrochemical Analysis: Landfill Leachate Plume

The laboratory physicochemical analysis of the leachate sample revealed high ionic strength and organic loading, with an EC of 21.73 ± 2.12 mS/cm, a TDS of 2273 ± 18.6 mg/L, a BOD_5 of 809 ± 15.5 mg O_2/L, and a COD of 2104 ± 18.9 mg O_2/L. The measured heavy metal concentrations were elevated,

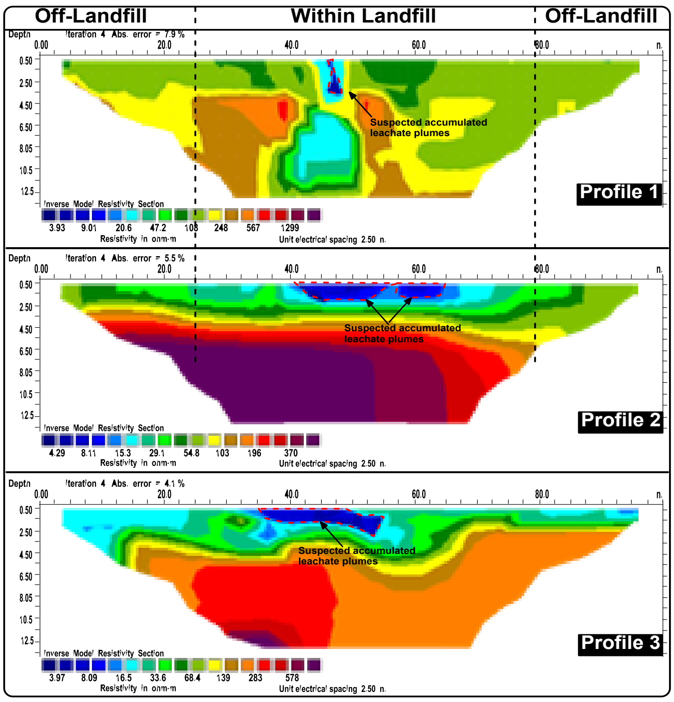

Fig. 3. 2D ERT Inverse Models of Profiles 1-3

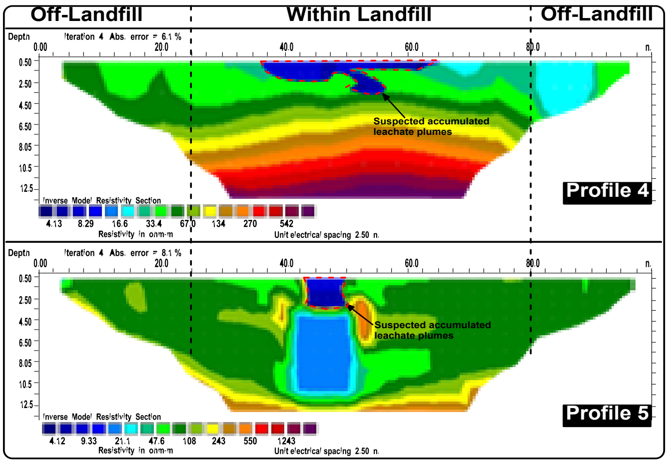

Fig. 4. 2D ERT Inverse Models of Profiles 4-5

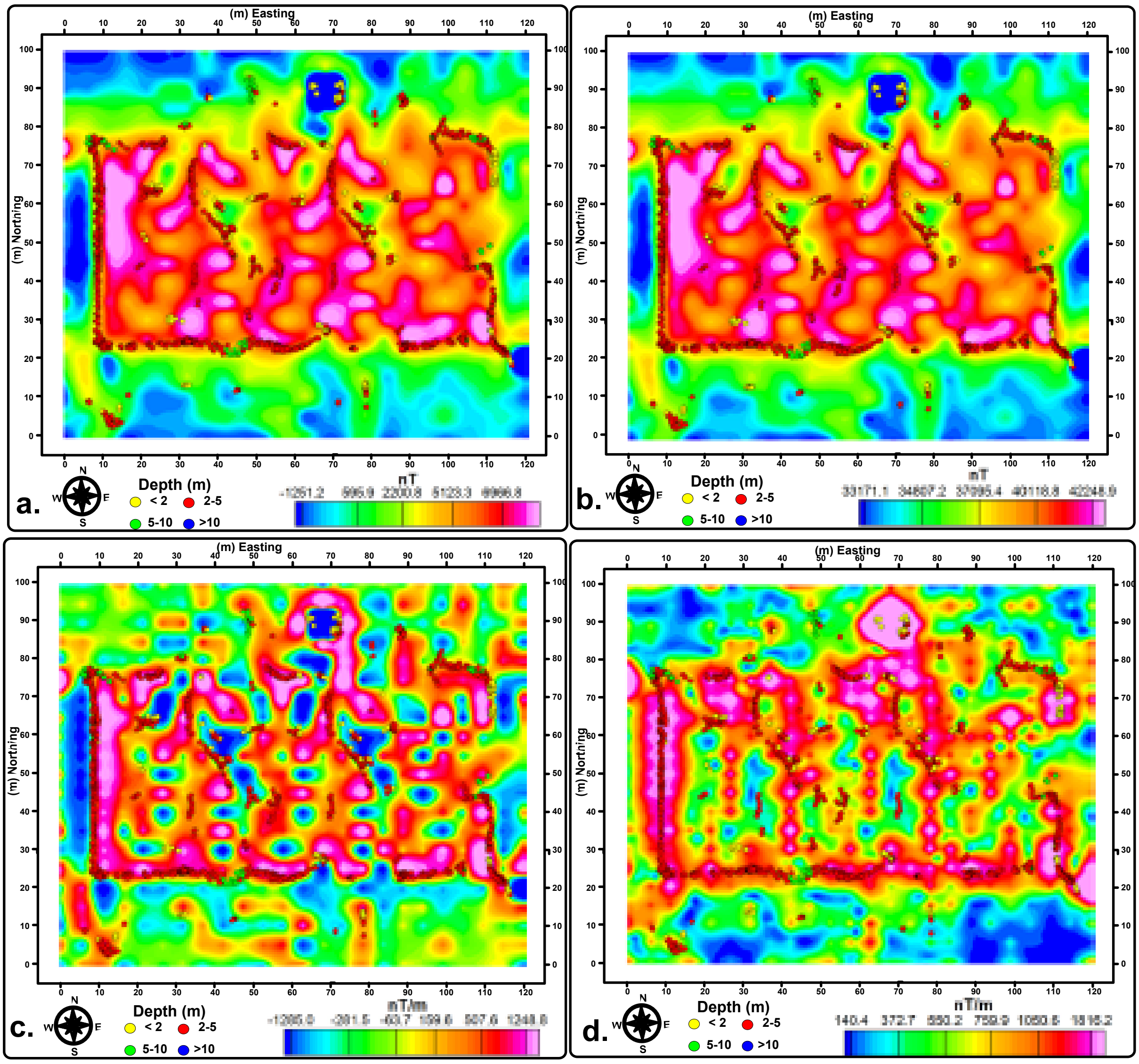

Fig. 5. The magnetic anomalies associated with LLPs within the site: (a) total magnetic intensity measurement, (b) residual map, (c) first vertical derivative map, and (d) analytical signal map

with Pb, Fe, Zn, and Cd values of 11.17 ± 1.81 mg/L, 12.31 ± 1.80 mg/L, 16.13 ± 3.11 mg/L, and 12.31 ± 1.80 mg/L, respectively (Table 3; Fig. 6). These values confirm that the same leachate sample and data set were used for both Table 3 and Fig. 6.

Discussion

This section discusses the environmental significance and implications of an integrated approach's results. The geophysical responses of the landfill materials were visualized using different techniques such as 2D ERT pseudo-section inversion, total magnetic intensity, residual map, first vertical derivative deconvolution, and analytical signal map alongside the leachate plume physicochemical analysis. Based on the electrical resistivity results, there is clear evidence of leachate plume occurrence at a horizontal distance of 36 – 65m along all the profiles at a depth of 0.0 m – 3.5 m as seen in the traverse profiles (Figs 3-4). This indicates that the landfill leachate plume has seeped into the landfill subsoils, which invariably affects the groundwater. However, the landfill leachate plume appears to have lesser impact on the surroundings. This is because horizontal distances of 0.0 – 36 m and 65 m – 100 m along all the traverse profiles show high resistivity contrast, mapped as off-landfill. The central regions of each profile exhibit high resistivity contrasts (anomalies) interprete as daccumulated leachate plume zones, which may be associated with highly biodegradable waste mixed with lateritic clay. Notably, a trend of increasing geoelectrical parameters was

Table 3: Physiochemical characteristic of the Investigated landfill leachate plumesuspected landfill leachate plume contaminants.

Parameter	EC	Fe	Pb	Zn	Cd	BOD_5	COD	TDS
Unit	mS/cm)	mg/L	mg/L	mg/L	mg/L	mg O_2/L	mg O_2/L	mg O_2/L
DLP	21.73±2.12	12.31±1.80	11.17±1.81	16.13±3.11	12.31±1.80	809±15.5	2104±18.9	2273±18.6

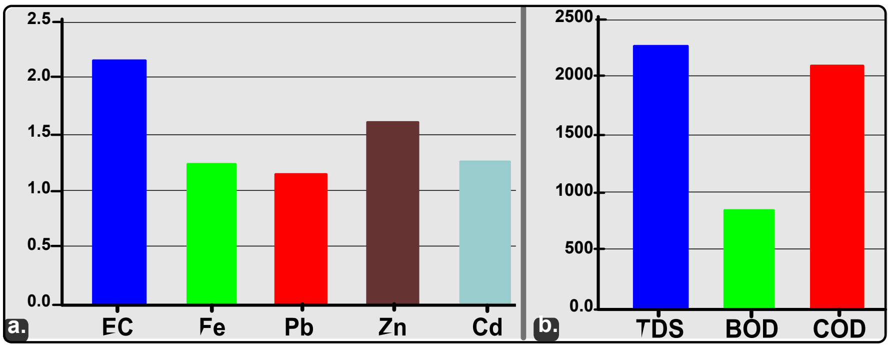

Fig. 6. Physicochemical characteristics of the investigated landfill leachate sample: (a) electrical conductivity, EC, in mS/cm; (b) heavy metals in mg/L; (c) BOD_s and COD in mg O_2/L; and (d) TDS in mg/L. The plotted values correspond to the same leachate data set presented in Table 3

observed with increasing distance from the landfill. Therefore, the leachate contamination within the upper 3.5 m may extend futrther in both vertical and horizontal directions over time due to migration. Consequently, the topsoil layer, also known as the engineering layer, stands at greater risk of failure due to the leachate infiltration. The 2D ERT technique adequately mapped the accumulated leachate plume to characterize the subsurface resistivity distribution across the landfill and its environs. This interpretation is consistent with recent geomechanical and underground-engineering studies showing that soil–foundation consolidation, anisotropic strength, tunnel-rock strength prediction, and spatially variable slope resistance are strongly controlled by coupled hydraulic, stress, and subsurface-property conditions (Yu et al., 2026; Zhou et al., 2026; Zhang et al., 2026; Zhao et al., 2026). For engineering assessment, such geophysical interpretation can be strengthened by real-time geotechnical strength prediction and hydromechanical stability analysis, especially where weak, water-rich, or contaminant-softened zones may reduce foundation resistance (Zhang et al., 2025; Wang et al., 2025).

The present results are consistent with recent studies showing that soil-water interactions, contaminant migration, and subsurface engineering performance are strongly controlled by coupled hydrogeological, geochemical, and geotechnical processes. For example, recent work on saline-land reclamation, flooded contaminant-enriched soils, geotechnical foundation assessment, and nature-based profiling of subsurface soil stiffness has emphasized that changes in soil-water chemistry and subsurface structure can significantly modify soil behaviour and environmental response (Hu et al., 2022; Wang et al., 2024a; Alalade et al., 2025; Fang et al., 2025). In the present study, the low-resistivity zone within the landfill, 2.8–9.0 Ωm, contrasts sharply with the off-landfill resistivity range of 29–150 Ωm, indicating that the landfill interior contains more conductive pore fluids and contaminant-rich materials than the surrounding ground. This interpretation is supported by the high EC, TDS, BOD_5, COD, and heavy-metal concentrations measured in the leachate sample. Recent studies on leakage-induced erosion, rapid drawdown of dikes, green-grey infrastructure resilience, contaminated-soil stabilization, artificial wetland hydrology, and dissolved-oxygen dynamics in aquifers further show that seepage, hydraulic gradients, contaminant chemistry, and soil treatment strategies must be evaluated together when assessing long-term environmental and engineering risks (Peng et al., 2025; Zheng et al., 2024; Di et al., 2026; Wang Fengchi et al., 2024b). Therefore, the integrated ERT, magnetic, and hydrochemical evidence in this study provides a stronger basis for interpreting the landfill as both an environmental contamination source and a geotechnical-risk zone.

The interpreted ground magnetic data delineated the extent and boundaries of LLPs accumulated within the landfill subsurface, generating the magnetic anomaly maps that identified the zone with elevated magnetic anomalies associated with the leachate plume. The results revealed distinct magnetic anomalies delineated as the leachate plume accumulation zone, extending from the surface into the soil. However, the shape of the anomalies produced by the analytic signal is similar to the first vertical divertive, and usually appeals in linear and spherical forms. The delineation of the plumes was achieved through the generation of magnetic anomaly maps, highlighting the zones with elevated magnetic anomalies corresponding to the presence of leachate contaminants. Furthermore, the depth estimation and visualization techniques enhanced the characterization of the vertical and horizontal distribution of LLPs, providing insights into the subsurface magnetic characteristics. The suspected leachate plume zones occur mostly at depth of 2 m – 5.0 m, while only few of them extend beyond 5 m vertically.

The concentrations of HMs in the leachate varies between 11.17 – 21.73 mg/L, which indicates high concentration with adverse potential effects on groundwater and soil, especially on the uppermost layer of the Earth's crust, which is widely regarded as the engineering layer. The biodegradability of the solid waste within a landfill are usually expressed by the ratio BOD_5 to COD. The BOD_5/COD is a vital parameter in assessing the water quality and waste treatment because it provides insight into the biodegradability of organic matter within water or wastewater (Alao, et al., 2023). For this study, the ratio of BOD_5 to COD for the landfill leachate plume was calculated to be 0.385, which is relatively low compared to the values reported in the previous studies. This suggests that the average fraction of organic matter contents in the investigated leachate plume is biodegradable. Therefore, a biological treatment methods such as bio-filtration, activated sludge is recommended as likely the most effective for treating the plume. The BOD_5/COD value also suggests average rainfall events on the solid wastes deposited at the landfill, which implies that the decomposition rate of the landfill waste increases moderately and subsequently yields more leachate plume contaminants. It is also important to recoganize that geochemical element concentrations varied seasonally, depending on the regional climate influence. While there is an average organic matter content in the landfill leachate, the HMs confirm the geophysical results and reinforcing the impacts of landfills on groundwater and soil pollution. In addition, LLPs contain dissolved heavy metals, organic matter, and salts. As leachate infiltrates the overburdened topsoil, it alters the geotechnical and geochemical properties of soils, increasing compressibility, reducing shear strength, and promoting subsidence (Khodary, et al., 2018). These alterations compromise the foundation-bearing capacity, which may introduce structural instability. Contaminant-laden leachate can facilitate pore fluid conductivity and clay mineral dispersion, especially in fine-grained soils. At the pore and mineral-interface scale, such degradation may be intensified by environmental cycling, ion desorption from clay minerals, gas–water interfacial processes, and the persistence of trace organic contaminants in environmental water systems (Wang et al., 2026; Long et al., 2025; Wu et al., 2026; Shi et al., 2025).

The further discussion emphasizes on the "stopping distance and depth" providing insights on how LLps can have a significant impact on groundwater quality because the leachate plume contaminants from unlined landfills or other waste disposal sites can flow horizontally and vertically to impact its surroundings. The stopping distance and depth refer to the distance and depth at which the plume is effectively contained or prevented from spreading further. The elevated levels of HMs in the leachate plume, ranging from 11.17 to 16.13 mg/L, together with EC of 21.7 mS/cm, indicate high contaminant loading and strong potential for continued groundwater-quality deterioration. However, lowcontaminant concentration in the leachate plume is low, it can help to contain the spread of the leachate plume and limit the extent of groundwater contamination. This can reduce the potential impact on water resources and ecosystems, and also minimize the need for costly remediation efforts. The stopping distance and depth of leachate plumes are largely determined by several factors, which include (i) hydrogeological properties, (ii) contaminant properties, (iii), groundwater flow dynamics, and (iv) site-specific conditions. Because such processes may evolve progressively, numerical frameworks for staged and cascading geotechnical failure provide useful analogies for modelling how changing subsurface geometry can amplify landfill-related ground instability (He & Qu, 2025; Zhao et al., 2026; Zheng et al., 2026).

First, the hydrogeological factors usually depnd on some subsurface properties such as the permeability and porosity of the subsoil and rock formations through which the leachate plume penetrates (Joseph, 2024), and these can significantly affect the stopping distance. Highly permeable materials increase the stopping distance of leachate plumes, while low permeability can reduce it. Based on the geophysical data, which shows high electrical resistivity in the topsoil, the stopping depth may be reduced. Secondly, the physical and chemical properties of LLPs such as their solubility, volatility, and reactivity, play a vital role in determining how far the leachate plumes can travel. For instance, high concentration of HMs present in the investigated sample LLPs indicates high contanminat strength, which potentially impacts both topsoil and groundwater systems as the degree of HM concentration may reflect leachate travel behavioour. Thirdly, basement slope, direction, and velocity of groundwater flow can also influence the movement and spread of leachate plumes. Factors such as hydraulic gradients and flow pathways can affect the stopping distance of the plume. Lastly, the specific characteristics of the landfill or waste disposal site, such as the site water table depth, topography, and the nature og landfill site (presence of liners/barriers), can significantly influence the stopping distance of LLPs (Joseph, et al 2025a; 2025b). In summary, the stopping distance/depth of leachate plumes is an important factor in determining the extent of groundwater contamination and the potential impact on water quality and ecosystems. It is crucial to manage the stopping distance effectively to protect groundwater resources. Understanding and considering these factors is essential for effectively managing and mitigating the impact of leachate plumes on groundwater quality. Site-specific assessments and monitoring can help to determine the potential stopping distance and inform appropriate remediation strategies.

Environmental and health Implications, and Future Directions

The environmental implications of this study focus on the impacts of LLPs on the groundwater and the uppermost topsoil layer, which is often regarded engineering foundation layer. The results show that the topsoil has experienced an influx of LLPs, weakening the soil-bearing capacity and quality, which eventually compromised the local aquifers. The 2D ERT detects and maps the LLPs within the depths of 0.0 – 3.5 m, showing leachate pathways that infiltrate the soil. This reinforces the impacts of the LLPs on soil, especially the engineering foundations, which affect the chemical compositions of the groundwater systems, placing public health on the high-risk radar as well. According to previous studies, when these LLPs flow into the ground soil, the integrity of the regional groundwater systems is compromised (Gogoi, et al., 2024; Xu, et al., 2024). According to a recent study, LLP is a powerful force that is a potential threat to topsoil engineering foundations (Alao, et al., 2023), a finding supported by some remarkable studies (Sunil, et al., 2009; Budi, et al., 2024).

The physicochemical results show high concentrations of HMs in the LLPs penetrating the uppermost layer of the Earth's crust, which influences bothsite electrical and hydraulic conductivities of the soil and eventually alters the chemistry of groundwater. This may reduce permeability, affecting drainage and water movement systems. In addition, infiltrating and contaminating the soil may cause swelling and shrinking potential due to ionic interactions within the soil. This implies that the LLPs can increase soil compressibility and impact foundation stability. Studies have also shown that LLPs can reduce the shear strength; as leachate pollutant content increases, cohesive force and the angle of internal friction decline (Budi, et al., 2024). A notable study shows that for every 10% leachate contamination, the shear strength of soil drops up to 50% (Sunil, et al., 2009). Therefore, leachate-accumulated topsoil experiences a sharp decrease in the shear strength of the soil due to the presence of leachate, which weakens the soil, affecting its load-bearing capacity.

The LLPs were noted to have considerably increased the permeability values for the regional topsoil, as reflected by electrical resistivity values across the landfill soil. The leachate plumes were also noted to have influenced the natural geophysical signature (resistivity) of the site, having the subsoil electrical resistivity between 2.8 – 9.0 Ωm within the landfill and 29 – 150 Ωm off the landfill. In addition, as the surveys distance from the landfill increased, a consistent decreasing trend of in apparent resistivity was noted. This outcome underscores the significance of excavating topsoil from abandoned landfills and refilling with lateritic soil for any serious civil engineering foundations. Additionally, adequate landfill lining is critical to prevent the percolation of leachate plumes into the subsoil and the groundwater, which has implications for engineering contructions. This study sheds light on the significant connections between the uppermost Earth's crust and LLPs while emphasizing the need for a thorough evaluation of engineering topsoil in leachate-accumulated zones before any serious engineering work and sustainable waste management practices. In summary, the major impacts of LLPs on the topsoil and geotechnical works as well as engineering foundation layer are as follow (i) reduction of the topsoil strength, (ii) altering of the ground soil hydraulic properties, (iii) alteration of groundwater chemistry, (iv) soil compressibility, (v) slope failures, (vi) variation in soil volume, (vii) electrical conductivity, and (viii) soil instability.

Addressing landfill leachate impacts on ground soil and groundwater requires a holistic approach, considering environmental and engineering aspects. Proper and adequate waste management and treatment are essential to safeguard water quality and preventions of adverse effects on the topsoil engineering foundations. Going forward, total soil excavation and refilling with lateritic soil, alongside with reinforced concrete foundation remain significant approaches proposed by the study alongside a robust modern sanitary landfill proposed for waste management (Omeiza and Diary, 2018; Li et al., 2025; Lin et al., 2025), and a strong media investment is recommended toeducate the public. Future landfill-risk management can also benefit from broader sustainability assessment, environmental knowledge management, green organizational practices, resilient material systems, sensor/log-based prediction, thermal mechanical infrastructure evaluation, and diagnostic monitoring frameworks for supporting long-term environmental and engineering decision-making (Tang et al., 2017; Zhang et al., 2020; Feng et al., 2023; Lyu et al., 2024; Liu et al., 2025). Additional engineered treatment options should include membrane-based separation for high-salinity organic wastewater streams and solidification/stabilization approaches for clayey soils exposed to landfill leachate, because both treatment performance and cured-soil properties depend strongly on contaminant chemistry and curing conditions (Xiao et al., 2019; Liu et al., 2024; Wang et al., 2025). Lateritic soil has been identified as the most preferred soil for geotechnical works (Ige & Baiyegunhi, 2022; Alao, 2024). Lateritic soil is rich in iron and aluminium oxides, and is known for its high stability and drainage properties. Transporting lateritic soil to the affected zones for backfilling the excavated region helps compact the soil layers to ensure a stable and uniform engineering foundation.

Concrete reinforcement systems can also help to prevent leachate plume from seeping into the ground while supporting the foundation engineering. The system can be used in several ways such as containment structures, landfill liners, and capping systems, in conjunction with other systems to prevent leachate from contaminating the ground. It is important to note that while reinforced concrete can be very effective at containing leachate plumes, it is not infallible because it can develop cracks over time as a result of improper construction, structural loading, or environmental stress. Therefore, regular inspections should be conducted to ensure the systems remain intact. In addition, to minimize environmental and human health risks, adequate chemical, biological, and physical processes are needed. Further studies should focus on developing a mathematical relationship between the stopping distance of leachate plumes and their impacts.

Conclusion

The LLPs from unlined landfills have significantly affected the groundwater and topmost layer of the Earth's crust and engineering foundations, with effect that persist for decades to centuries. Understanding the temporal and spatial dynamics of leachate flow is crucial for monitoring, risk assessment, and resource management. Based on geophysical and physicochemical data, evidence of leachate plume occurrence is evident at depth of 0.0 m – 5.0 m. Electrical and magnetic data show a high contrast within the landfill, with resistivity values ranging from 2.8 Ωm to 9.0 Ωm and TMI values ranging from 37500 nT to 43510 nT within the landfill, while off-landfill values range from 29 Ωm to 150 Ωm for resistivity and from 31,095 nT to 36500 nT for TMI. The physicochemical compositions of the landfill leachate plume shows high concentrations of HMs (11.17±1.81 mg/L to 16.13±3.11 mg/L) and EC (21.73±2.12 mS/cm). The high levels of biodegradable organic matter, such as BOD_5 (809±15.5 mg O_2 O_2/L), COD (2104±18.9 mg O_2 O_2/L), and TDS (2273±18.6 mg/L) highlight potential health and environmental risks. The analysis shows that LLPs have increased topsoil permeability, influencing the natural geophysical signature (resistivity) of the site. As the survey distance from the landfill increased, a consistent decrease in apparent resistivity) values was noted, underscoring the importance of excavating the topsoil of abandoned landfills for civil engineering foundations. In addition, groundwater quality and soil integrity are significantly affected. Combining physicochemical data with electrical resistivity and ground magnetic data for environmental risk assessment, a a comprehensive understanding of the landfill site and leachate plume behaviour can be achieved. Future research should include a broader health risk assessment using water samples from the landfill vicinity to understand heavy metal contamination in drinking water better.

Declaration

Ethical Approval: I declare that this research is original work carried out by all the authors and that no part of this work has been previously published in any journal. All information provided in this work has been duly acknowledged in the text and the references provided.

Consent to Publish: I have read, understand, and agree with the provided information and the terms of the Journal

Declaration of Conflict Interest: No conflicting interest

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Data Availability Statement: The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

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