Post-Closure Heavy-Metal Contamination, Ecological and Human-Health Risk Assessment, and Phytoremediation Potential at Mehmood Booti Landfill, Lahore

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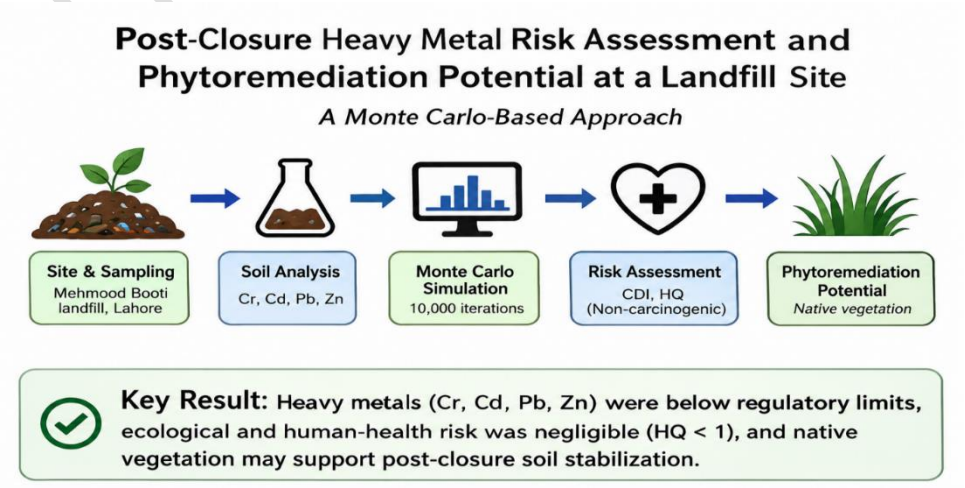
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Graphical Abstract



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Abstract

The uncontrolled disposal of municipal solid waste can leave residual heavy metals in soil after landfill closure. This study assessed near-surface soil quality and screening-level ecological and human-health risks at the post-closure Mehmood Booti landfill in Lahore, Pakistan. Five independent soil samples were collected from 30–90 cm depth and analyzed for chromium (Cr), cadmium (Cd), lead (Pb), and zinc (Zn), together with selected physicochemical properties. Zinc showed the highest reported mean concentration (8.46 ± 1.11 mg/kg), while Cd was below the reporting limit. The reported Cr and Pb readings are below the stated method detection limits and are therefore treated cautiously rather than as fully quantified concentrations. Regulatory screening comparisons indicated that Zn was below the selected PEQS screening value. The human-health assessment focused on the adult soil-ingestion pathway. An empirical Monte Carlo simulation of 10,000 iterations was constructed. The resulting Zn HQ distribution had P5 = 3.24 × 10−5, P50 = 3.74 × 10−5, and P95 = 4.50 × 10−5, and no simulated iteration exceeded HQ = 1. This is associated with the fact that the native phytoremediating species such as *Chrysopogon zizanoides and Prosopis juliflora* may provide natural stabilization of the heavy metals. The findings provide a screening-level assessment of the sampled near-surface soil and support continued monitoring of deeper soil, groundwater, and vegetation.

Keywords: Municipal solid waste; Soil quality; Zinc; Hazard quotient; Monte Carlo simulation; Screening-level assessment; Closed dumpsite; Pakistan

1. Introduction

Global projections indicate that municipal solid waste generation already exceeds 2.01 billion metric tons annually, and may rise to 3.40 billion metric tons by 2050 (Maqsoom et al., 2020). Closed landfills often pose long-term environmental liabilities due to residual soil contamination. In many cases, they have been repurposed into recreational or green spaces

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without sufficient scientific evaluation of ecological recovery or health risks (Alam, Chaudhry, Mahmood, et al., 2021).

In recent years, Municipal Solid Waste (MSW) has become one of the most notable environmental issues of the 21st century. Soil pollution around landfill sites, which is affected by leachate, poses a significant problem in MSW management, particularly in developing nations, where obsolete technologies and insufficient pollution control measures may worsen pollution levels (Khan et al., 2021). High population growth rate, population urbanization, and industrialization are among the factors that have led to the production of high quantities of solid waste. Poor waste collection and treatment services, such as open dumpsites and inadequate scientific disposal, are another major problem that has severe effects on soil and the environment. Solid waste management is ineffective and poorly developed in Pakistan, and the largest cities, such as Lahore, produce thousands of metric tons of waste every day. This waste is largely disposed of in landfills, the majority of which are not environmentally engineered and are devoid of good-quality lining, leachate, and gas collection and control systems. These unregulated dumpsites pollute the soil and water, thereby affecting ecological systems and people's health (Alam, Chaudhry, Ahmad, et al., 2021; Jadoon et al., 2025; Pakar et al., 2025; Romeh & Ismail, 2026).

In Pakistan, most MSW disposal sites are factually operated without proper liners and leachate collection systems, causing multifaceted contamination legacies that persist for a long duration, even after closure, and creating uncertainties for urban redevelopment and public exposure. The Mehmood Booti open dumping site was shut in 2016 and has just recently gone through vegetative rehabilitation; however, the transition to green space has not resolved the residual contamination dynamics.

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Mehmood Booti, one of the oldest landfills in Lahore, was operated in 1998 and has already handled more than 13.14 million metric tons of MSW. It is approximately 16 ha in area and receives a large amount of waste from Lahore (Alam et al., 2017; Alam, Chaudhry, Mahmood, et al., 2021; Mary et al., 2023). The landfill is surrounded by low-income communities, where poor environmental conditions expose people to health risks. All these wastes have formed dumps that are as high as 80 feet above the surface (Vongdala et al., 2019). The leachate produced during the rainy season as a result of the decomposed waste percolates into the soil and may contaminate the groundwater and surface freshwater bodies in the vicinity. In the long run, such pollutants, especially heavy metals, may accumulate in the soil, thereby causing damage to the long-term ecology (Alam, Chaudhry, Ahmad, et al., 2021).

Common pollutants found in the landfill site are leachate, heavy metals, such as Cr, Pb, Cd, and Zn are especially dangerous (Smol et al., 2020). Heavy metals are non-biodegradable and therefore persist in soils and ecosystems for extended periods (Smol et al., 2020). Some of these heavy metals e.g., Zn are although essential in trace amounts as micronutrients, excessive levels are toxic to plants, animals, and human beings (Alam et al., 2017; Alam, Chaudhry, Mahmood, et al., 2021). In particular, Pb and Cd do not have biological functions and are fatally poisonous in low dose (Komal et al., 2024; Mohamed et al., 2009; Rafique et al., 2025). Such metals have the possibility of disrupting the functioning of soil microorganisms, reducing the soil fertility and invading into the food chain as ingested by plants, with potentially hazardous health consequences, including neurological complications, developmental issues, and cancer (Alam et al., 2017; El-Beltagi & Mohamed, 2010; Jadoon et al., 2025).

Long-term MSW behavior is also important when interpreting post-closure contamination. Waste degradation changes moisture conditions, organic-matter breakdown, leachate chemistry, contaminant mobility, settlement, and the mechanical stability of the waste mass.

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Recent experimental work demonstrates that degradation characteristics and leachate properties respond jointly to moisture content, temperature, organic-matter content, and degradation time, emphasizing that landfill behaviour continues to evolve after waste placement (Zheng et al., 2022). Similarly, experimental work on MSW shear strength shows that degradation time and interacting environmental and compositional factors can alter the mechanical properties relevant to landfill stability (Muneer et al., 2026). These findings provide an important long-term context for post-closure sites such as Mehmood Booti, where changes in waste degradation and settlement may influence the movement and exposure potential of residual contaminants.

Though extensive literature has been done on heavy metal contamination active landfill environment, but few research assesses persistence of contaminants, ecological reduction, as well as phytoremediation after landfill closure, especially in developing urban contexts. Moreover, most of the Pakistani risk appraisals are non-probabilistic and is not deterministic and exposes parameters to variations, likewise establishing a disconnect between risk estimation and communication of uncertainty to policy.

The working hypothesis is that residual heavy-metal concentrations in the closed landfill's near-surface soils remain spatially variable, while ecological and human-health screening results depend strongly on the analytical detection limits, reference values, and exposure assumptions. The present study evaluates this hypothesis using the five available field samples and explicitly recognizes the limitations imposed by the small sample size, the restricted analyte set, the Cr/Pb detection-limit issue, and the absence of deeper-soil and groundwater measurements.

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2. Methodology

2.1 Study Area Description

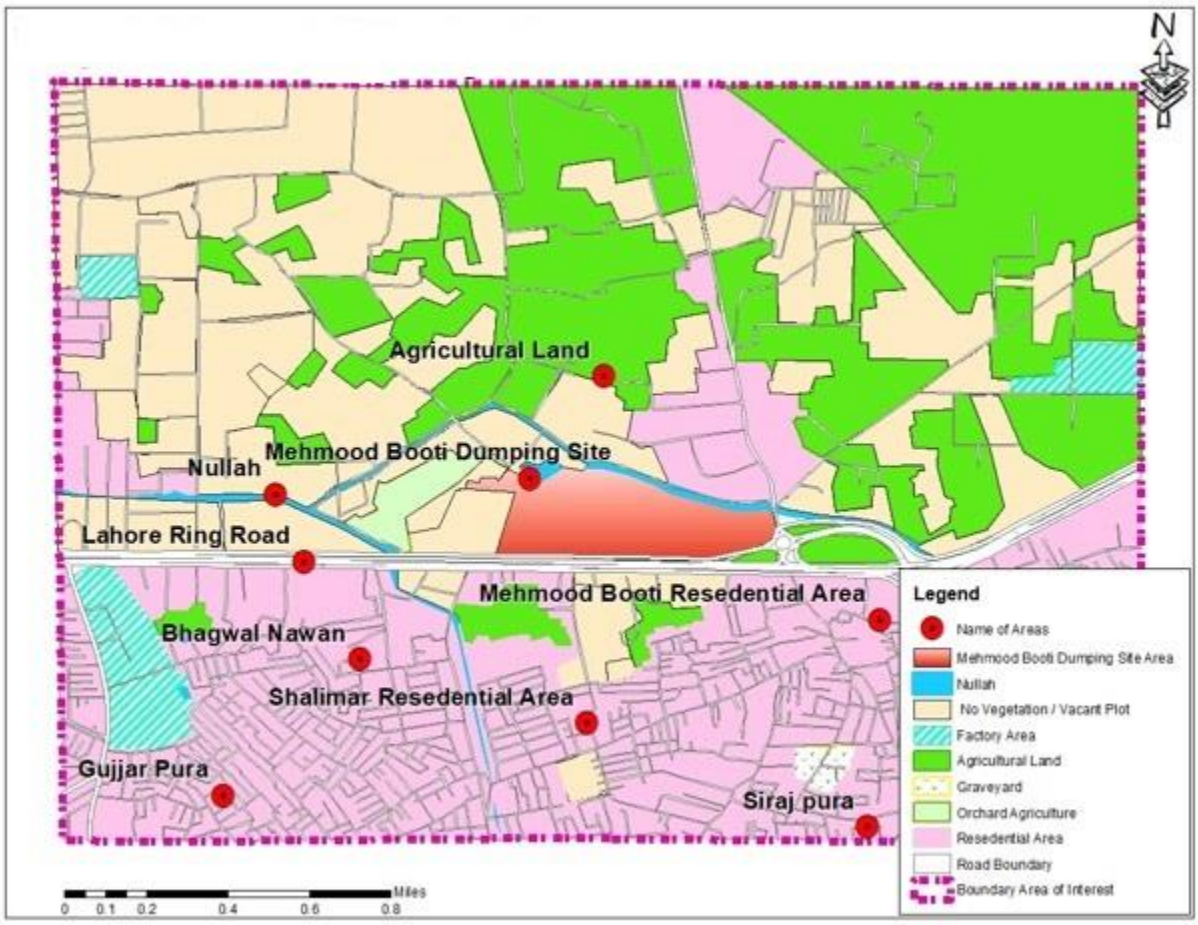
This study was conducted at one of the oldest disposal sites, named Mehmood Booti, which is located near the Ring Road in Lahore (Figure 1). It has been in operation since 1998, and approximately 13.14 million metric tons of waste has been dumped at the 16-hectare disposal site. Between 55% and 60% of the waste is composed of biodegradable stuff. The land area surrounding Mehmood Booti is more affordable than that of any other part of Lahore. Most of the residents living close to such landfill sites are low-income and unaware of the risks posed by nearby waste. The vast piles of rubbish can be seen from a distance because the collected waste has reached a height of 80 ft above ground level. During the rainy season, contaminated leachate is generated, which seeps into the underground and surface water supplies.

To date, four prior studies have been conducted at the Mehmood Booti site. Haydar et al., (2012), assessed the dumping site's effect on nearby groundwater quality, reporting no significant deviation from standard limits. Alam et al. 2017 conducted an ecological risk assessment covering leachate, groundwater, and a community health survey, finding leachate parameters above WHO limits and respiratory problems as the most common health complaint. Alam et al., (2021) subsequently applied a Conceptual Framework Model with LandGEM modeling to estimate methane and NMOC emissions. Most recently, Mary et al., (2023) compared heavy metal contamination and health risk in groundwater at Mehmood Booti and Lakhodair, reporting a higher perceived health risk (35%) among Mehmood Booti residents.

However, each study addressed only a single risk component, and no integrated, site-wide risk assessment has been conducted at Mehmood Booti post-closure. This site was therefore selected because it is one of the oldest and largest legacy disposal sites in Lahore, has recently reached post-closure status, lacks any prior integrated risk assessment, lies close to low-income

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144 residential areas with limited risk awareness, and offers direct regulatory relevance for future
145 land-use planning and remediation decisions.



146

147 Figure 1: Map of Study Area: Mehmood Booti Dumping Site Lahore District

148 **2.2 Vegetation Assessment**

149 The site was visited during the day in order to evaluate the surrounding environment. Plants
150 occupied a significant portion of the site and were used as phytoremediators. They grew to
151 cope with the soil of the site, which was contaminated, and contained heavy metals. The
152 different species of plants were different was found with the help of the manager of the place.

153 **2.3 Sample Collection**

154 The sampling depth of 30–90 cm was selected to represent the near-surface biologically active
155 zone, defined here as the soil layer in which root activity, microbial processes, surface-soil

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reactions, and direct human/ecological contact are concentrated. Five independent field soil samples were collected between 08:00 and 12:00 h from spatially separated areas of the historical waste-disposal footprint. The five field samples, not the analytical digestion replicates, are the independent sampling units. The available records do not provide sufficient independent observations per location for location-based inferential testing.

Five soil samples were randomly collected from the Mehmood Booti landfill site between 08:00 and 12:00 h, at depths of 30–90 cm below the surface, using a hand auger and soil probe. Samples were placed in labeled polyethylene zipper bags following U.S. Environmental Protection Agency (USEPA) protocols to prevent contamination. The coordinates and depth of each sampling point were recorded and are listed in SI Table 1.

2.4 Sample Preparation and Analysis

After mixing and gradually homogenizing the samples, they were sieved using a 2-mm mesh screen. The samples were air-dried and heated to approximately 40 °C for 30 min in an electric oven. The fine powder was then stored at room temperature for digestion. Physicochemical and heavy metal analyses were performed. The physicochemical parameters included pH, electrical conductivity (EC), moisture content, and soil texture.

An atomic absorption spectrophotometer (Model AAS 6200) was used to analyze the heavy metals. This was done by weighing 1 g of oven-dried sample on a weighing balance and placing it in individual 250 mL beakers in which 15 mL of aqua regia prepared from concentrated HNO_3 and 35% HCl in a ratio of 3:1 was added. The combination was then digested at 70 °C until the solution became translucent. The resulting solution was filtered through Whatman filter paper into a 50 mL volumetric flask and diluted to the mark using deionized water. A sample solution was analyzed for the concentrations of Cr, Zn, Cd, and Pb using an atomic absorption spectrophotometer.

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Quality assurance and quality control (QA/QC) procedures included certified reference materials (CRM), method blanks, and duplicate samples analyzed at a frequency of 10% of the total sample batch. Recovery rates for all metals were within the reported acceptable range of 85–115%. The reported method detection limits were 0.05 mg/kg for Cr, 0.02 mg/kg for Pb, 0.01 mg/kg for Cd, and 0.10 mg/kg for Zn. For Cr and Pb concentrations below these stated detection limits, those two elements are treated as below-LOD/ non-quantifiable for quantitative risk interpretation in the revised manuscript. Cd was also below the reporting limit. Digestions were performed in triplicate for analytical precision; these triplicates are not treated as independent field replicates.

A numerical Potential Ecological Risk Index (PERI) was not retained in the final analysis because the available records do not provide a defensible local or regional geochemical background dataset. PERI requires a measured concentration divided by an appropriate background/reference concentration; regulatory screening limits such as WHO or PEQS values are not interchangeable with natural geochemical background. Regulatory values are therefore used only for compliance/screening comparisons.

2.5 Environmental Risk Assessment

Environmental risk assessment was conducted using various geostatistical techniques to identify the sources—whether natural or anthropogenic—and to evaluate the extent of heavy metal pollution impacting humans and the environment. This study utilized the potential ecological risk index (PERI) and the human health risk assessment model.

2.6 Potential Ecological Risk Index (PERI)

The PERI method was used to analyze environmental harm issues in an investigation into the ecological health implications of waste management activities (IRIS, 2019). This method was also used by (Okoye, 2023) to assess potential and environmental hazards from heavy metals.

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The potential ecological risk for each metal (Er) and the overall risk index (RI) were calculated using the following equations:

$$\boldsymbol{Er = Tr\ x\ Cf} \text{.....(Eq. 1)}$$

$$RI=\sum Er \text{---------- (Eq 2)}$$

Here, Tr is the toxicity response factor specific to each metal. Cf refers to the contamination factor of a metal. Er represents the ecological risk potential of each metal, whereas RI is a cumulative ecological risk potential index that shows the total danger for all metals tested.

2.7 Chronic Daily Intake (CDI)

CDI stands for chronic daily intake. It is an effective measure for determining the long-term effects of exposure to soil pollutants. Typically, factors such as body weight, frequency, duration, and pollutant concentration are used to determine CDI. It aids in assessing potential health risks associated with persistent soil contamination. It was calculated using the following formula:

$$CDI = (Csoil \times IR \times ED \times EF) / (BW \times AT) \text{ ---------- (Eq. 3)}$$

The ecological screening assessment compares measured concentrations with the selected regulatory guideline values.

Csoil is the concentration of the pollutant in soil (mg/kg); IR is the soil ingestion rate (mg/day); ED is the exposure duration (years); EF is the exposure frequency (days/year); BW is body weight (kg); and AT is the averaging time (days).

A limited empirical Monte Carlo analysis was conducted to quantify uncertainty in the Zn soil-ingestion screening result without creating additional laboratory observations. The five

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measured Zn concentrations (9.30, 9.85, 7.10, 8.20, and 7.85 mg/kg) were assigned equal empirical probability (0.20 each) and resampled with replacement for 10,000 iterations. No parametric distribution was fitted because only five independent field observations were available. The exposure parameters IR = 100 mg/day (1.0 × 10−4 kg/day), ED = 20 years, EF = 350 days/year, BW = 70 kg, and AT = 7,300 days were used for the non-carcinogenic endpoint. The Zn reference dose was 0.3 mg/kg-day. CDI and HQ were calculated for every iteration. The random seed was 20260822 and the complete iteration-level data are provided in Supplementary Data S1. This simulation represents empirical uncertainty from the available concentration dataset and is not a substitute for additional field sampling or laboratory measurements.

For the adult soil-ingestion scenario, IR = 100 mg/day was converted to 1.0 × 10−4 kg/day when Csoil was expressed in mg/kg, ED = 20 years, EF = 350 days/year, BW = 70 kg, and the non-carcinogenic averaging time was AT = ED × 365 = 7,300 days. Because Cr, Pb, and Cd were below the stated detection/reporting limits, quantitative CDI/HQ interpretation is restricted to Zn. For Zn (8.46 mg/kg mean concentration), the deterministic adult soil-ingestion calculation gives CDI ≈ 1.16 × 10−5 mg/kg-day and HQ ≈ 3.9 × 10−5 using the RfD reported in the study. This value is below 1 and should be interpreted only as a screening estimate for the stated exposure pathway.

Where:

- IR is the ingestion rate (100mg/ day),
- ED is the duration of exposure (20 years),
- EF is the frequency of exposure (350 days/year),
- AT is the average time of exposure

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For non-carcinogenic risk (HQ), AT = ED × 365 = 20 × 365 = 7,300 days. A separate lifetime averaging time would be required for a validated carcinogenic-risk assessment; no quantitative carcinogenic-risk conclusion is retained here.

2.8 Hazard Quotient (HQ)

Hazard Quotient (HQ) was calculated using Eq. (4):

Plant tissue samples (root and shoot) were not collected in this study; therefore, bioconcentration factor (BCF = metal in shoot/metal in soil) and translocation factor (TF = metal in shoot/metal in root) could not be calculated. The phytoremediation discussion is consequently qualitative and is based on vegetation observed at the site together with literature evidence on the metal tolerance or uptake capacity of the identified species. The occurrence of Chrysopogon zizanioides, Prosopis juliflora, Bauhinia variegata, and Conocarpus erectus does not by itself demonstrate site-specific Pb, Cd, or Zn phytoextraction or phytostabilization. Future studies should analyze matched soil, root, and shoot tissues across seasons and calculate BCF and TF to determine actual metal uptake and translocation under Mehmood Booti conditions.

CDI is the chronic daily intake (mg/kg/day), and RfD is the reference dose of the compound (mg/kg/day). An HQ value of < 1 indicates non-hazardous exposure (ISPRA, 2013).

Numerical presentation note: values for pH and other routine physicochemical parameters are reported at practical precision, whereas very low Cr and Pb concentrations retain sufficient decimal places to avoid rounding them to zero. Metal values should not be rounded to one decimal place when doing so would obscure concentrations near the analytical detection limit.

The cancer risk effect (CRE) or carcinogenic risk to humans due to the ingestion of contaminated soil through direct and indirect contact was calculated using Eq. (5):

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271 $$CRE = CDI \times SF \quad \text{---------- (Eq 5)}$$

272 where SF is the slope factor (1/kg/day), representing the upper-bound estimate of risk per unit
273 dose increase (Maqsoom et al., 2020) to estimate the probabilities of risk at various exposure
274 levels. CRE < 10-6 was considered negligible. Because total chromium (not speciated Cr (VI))
275 was measured in this study, the carcinogenic slope factor was applied assuming a conservative
276 fraction of total Cr as Cr (VI), following standard USEPA practice for sites lacking speciation
277 data; consequently, the resulting CRE for Cr should be interpreted as a conservative, upper-
278 bound estimate rather than a speciation-confirmed carcinogenic risk value.

279 Plant species were identified at the landfill site with the assistance of the site's compost
280 manager and the mobile application, PlantNet, for quick digital recognition. Their potential as
281 phytoremediators was discussed in the context of soil restoration.

282 Vegetation tolerant of disturbed environments may contribute to surface stabilization, erosion
283 control, and dust suppression. However, the presence of vegetation at the closed disposal area
284 does not demonstrate site-specific phytoextraction or phytostabilization. *Chrysopogon*
285 *zizanoides, Prosopis juliflora, Bauhinia variegata*, and *Conocarpus erectus* are therefore
286 discussed as potential species of interest for future phytoremediation experiments rather than
287 as proven remediation agents at this site.

288 **3. Results and Discussion**

289 Heavy-metal contamination can affect soil quality, ecological functioning, and human health
290 when concentrations are sufficiently elevated and exposure pathways are present. In the present
291 near-surface soil dataset, the measured Cr, Cd, Pb, and Zn concentrations were low relative to
292 the selected regulatory screening values. Zinc had the highest concentration among the
293 analyzed metals, while Pb and Cr occurred at much lower concentrations and Cd was below

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the verified reporting level. These results describe the sampled soil layer and should not be extrapolated to deeper soil, groundwater, or the buried waste mass.

The five field observations are presented descriptively in Table 2. Because independent replicate groups were not available for each location, inferential p-values are not reported. This avoids treating laboratory analytical triplicates as independent spatial observations.

The concentrations of four metals (Cr, Pb, Cd, and Zn) in Mehmood Booti soil samples were examined to determine their distribution, sources, and ecological effects. The heavy metal analytical findings are shown in Table 1. Zn had the highest concentration (8.46 ± 1.11 mg/kg) among the four metals.

Table 1: Physicochemical Analysis and Heavy Metals (with Mean ± SD) of soils at Mehmood Booti Dumping Site

Parameter	Std. / Range	S1	S2	S3	S4	S5	Mean ± SD
pH	5.5–8.0	6.5	7.0	5.8	6.3	6.9	6.6 ± 0.7
Organic Matter (%)	–	2.8	3.2	1.9	2.5	2.0	**2.48 ± 0.5**
Moisture Content (%)	5–20%	12.5	14.0	10.0	11.0	13.5	**12.2 ± 1.5**
Texture	–	Sandy Loam	Clay	Sandy	Sandy Loam	Loam	–
Chromium (mg/kg)	150	0.0075	0.0081	0.0060	0.0068	0.0062	0.00692 ± 0.00088
Cadmium (mg/kg)	3	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Lead (mg/kg)	60	0.0155	0.0162	0.0124	0.0140	0.0134	0.0143 ± 0.00155
Zinc (mg/kg)	200	9.30	9.85	7.10	8.20	7.85	**8.46 ± 1.11**

The reported Cr and Pb instrument readings were below the stated method detection limits and are therefore treated as below-LOD/non-quantifiable for risk interpretation. Cd was also below the reporting limit. Zinc had the highest reported mean concentration (8.46 ± 1.11 mg/kg), which remained below the selected PEQS screening value of 200 mg/kg. These comparisons

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are screening-level findings for the sampled near-surface soil and do not establish the absence of contamination at depth.

Soil physicochemical properties can influence metal mobility and plant establishment. The five samples had pH values of 5.8–7.0, organic matter of 1.9–3.2%, and moisture contents of 10–14%. These observations provide context for the sampled near-surface soil. The available data do not permit a causal attribution of Zn concentration to pH or organic matter, and they do not demonstrate natural attenuation or site-specific phytoremediation.

The lead value is below the stated method detection limit and is therefore not treated as a fully quantified concentration. Zinc had the highest reported mean concentration (8.46 ± 1.11 mg/kg) and remained below the selected PEQS screening value (200 mg/kg). These results support a low screening-level concentration profile but do not establish overall environmental safety.

Soil physical factors include pH that evaluates the soil's acidity or alkalinity and influences nutrient availability. Moisture content indicates how much water is available to plants in the soil. Electrical conductivity (EC) is employed to gauge the salinity levels of the soil. Most plants prefer soils with slightly acidic to neutral pH levels (5.8–7.0). Results show that few samples of soil exhibited the highest percentage of organic matter (1.9%–3.2%), which contributed to improved soil fertility and nutrient cycling. The soil retained water necessary for the growth of plants and microbes at levels between 10–14%. The current findings show that the soil samples were identified as loamy, clayey, sandy, and silty. The physicochemical attributes of the soil directly influence the mobility and bioavailability of heavy metals at this post-closure dumping site. As reported above (pH 5.8–7.0; Table 1), the soil is close to neutral, which would favor moderate bioavailability of Zn and hence its uptake by roots. Adsorption on clay particles and organic matter (1.9–3.2%) may also contribute to Zn retention in the soil;

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however, these are possible mechanisms rather than demonstrated causes, and they do not establish natural attenuation or site-specific phytoremediation.

Variability among the five field samples is described using the reported means, standard deviations, and ranges. Soil texture is categorical and is therefore not assigned a numerical standard deviation. The observed variability should be treated as descriptive because the sample size is small.

Table 2: Descriptive Comparison Across the Five Sampling Points

Parameter	S1	S2	S3	S4	S5	Mean ± SD	Interpretation
pH	6.5	7.0	5.8	6.3	6.9	6.50 ± 0.51	Descriptive only
Organic matter (%)	2.8	3.2	1.9	2.5	2.0	2.48 ± 0.54	Descriptive only
Moisture content (%)	12.5	14.0	10.0	11.0	13.5	12.20 ± 1.58	Descriptive only
Cr (mg/kg)	0.0075	0.0081	0.0060	0.0068	0.0062	0.00692 ± 0.00088	Below stated LOD; descriptive instrument readings
Pb (mg/kg)	0.0155	0.0162	0.0124	0.0140	0.0134	0.01430 ± 0.00155	Below stated LOD; descriptive instrument readings
Zn (mg/kg)	9.30	9.85	7.10	8.20	7.85	8.46 ± 1.11	Quantitative concentration
Cd (mg/kg)	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	Not quantified

The measured concentrations were below the regulatory screening values used for comparison in this study. These comparisons indicate low concentrations in the sampled near-surface soils; they do not demonstrate the absence of contamination in deeper soil, landfill waste, leachate, or groundwater. The ecological-risk interpretation is also dependent on the verified geochemical background/reference concentrations used in the PERI calculation. Accordingly,

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the results should be interpreted as a near-surface screening assessment rather than a whole-landfill safety determination.

3.3 Environmental Risk Assessment

The Environmental Risk Assessment (ERA) of a soil sample entail determining the presence of contaminants and their possible influence on human health and the ecosystem.

3.3.1 Contamination Factor and Ecological Risk Index

The human-health assessment is restricted to the soil-ingestion pathway. Dermal and inhalation exposure were not evaluated.

Table 3: Detection of Contamination Factor of Soil Sample

Metal	Mean concentration (mg/kg)	Selected screening value (mg/kg)	Screening interpretation
Cr	<LOD*	150	Below screening value; quantitative value below LOD is not retained
Pb	<LOD*	60	Below screening value; quantitative value below LOD is not retained
Cd	<LOD	3	Below reporting limit
Zn	8.46	200	Below screening value

The adult parameters IR = 100 mg/day, ED = 20 years in the revised manuscript, EF = 350 days/year and BW = 70 kg. For concentrations in mg/kg, 100 mg/day must be converted to 1.0×10^-4 kg/day. For non-carcinogenic effects, AT = ED×365 = 7,300 days; the 7,300-day value appearing for Cd in the earlier table was inconsistent and has been corrected to 7,300 days. The risk interpretation is therefore limited to this adult soil-ingestion scenario and should not be generalized to total residential exposure.

Regulatory screening comparisons indicate low measured concentrations in the sampled near-surface soils. These results do not demonstrate natural attenuation or overall landfill safety

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because only one sampling event was available and deeper soil, groundwater, leachate, and temporal trends were not assessed.

Native vegetation at the site may contribute to surface stabilization and dust/erosion control, but its presence does not demonstrate site-specific phytoremediation. The study did not measure plant-tissue metal concentrations, so uptake, translocation, phytoextraction, and phytostabilization remain unverified. All quantitative figure interpretations are restricted to the four analyzed metals (Cr, Cd, Pb, and Zn).

The present results provide a screening-level indication for the evaluated soil-ingestion pathway and sampled near-surface soils. They should not be interpreted as evidence of overall landfill safety. Future human-health assessments should include dermal contact and inhalation pathways, deeper soil profiles, groundwater, seasonal variation, and site-specific child and adult exposure parameters.

Native vegetation at the site may contribute to surface stabilization and dust/erosion control, but its presence does not demonstrate site-specific phytoremediation or contaminant removal. The human-health result is a screening-level Zn assessment for the adult soil-ingestion pathway. Figure 4 presents the empirical Monte Carlo uncertainty distribution for Zn HQ. Continued monitoring is recommended because deeper soil, groundwater, and temporal trends were not assessed.

The human-health assessment was restricted to the adult soil-ingestion pathway. Because Cr and Pb were below the stated method detection limits and Cd was <LOD, only Zn was retained for quantitative CDI and HQ interpretation. Using Csoil = 8.46 mg/kg, IR = 1.0 × 10−4 kg/day, ED = 20 years, EF = 350 days/year, BW = 70 kg, and AT = 7,300 days, the deterministic Zn CDI is 1.16 × 10−5 mg/kg-day and HQ is 3.86 × 10−5 (RfD = 0.3 mg/kg-day) (Muneer et al., 2026).

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The corrected deterministic calculation is reproduced in Table 3. To characterize concentration uncertainty without fabricating additional measurements, 10,000 empirical Monte Carlo iterations were performed by resampling the five observed Zn concentrations with replacement and assigning equal probability to each observation. The resulting Zn CDI had P5 = 9.73 × 10−6, P50 = 1.12 × 10−5, and P95 = 1.35 × 10−5 mg/kg-day. Zn HQ had P5 = 3.24 × 10−5, P50 = 3.74 × 10−5, and P95 = 4.50 × 10−5. No simulated iteration exceeded HQ = 1. The full iteration-level dataset and input parameters are provided in Supplementary Data S1.

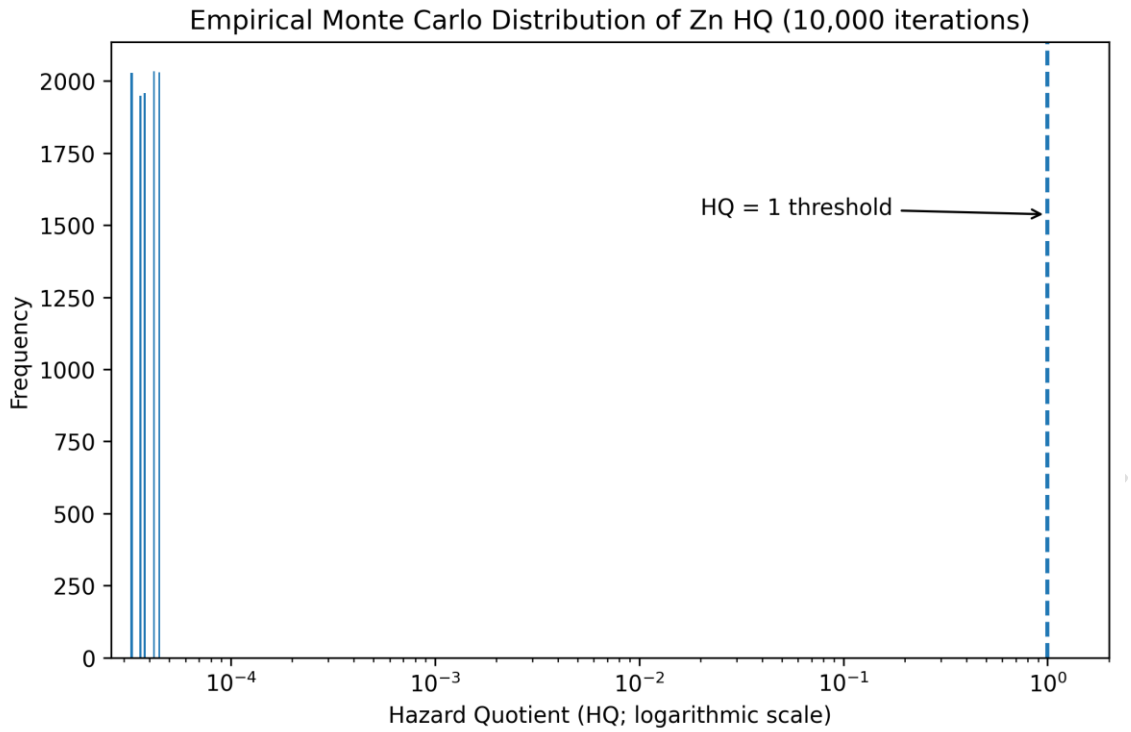
The quantitative adult soil-ingestion calculation retained in the revised analysis is restricted to Zn because Cr and Pb are below the stated method detection limits and Cd is <LOD. Using Csoil = 8.46 mg/kg, IR = 1.0×10−4 kg/day, ED = 20 years, EF = 350 days/year, BW = 70 kg, and AT = 7,300 days gives Zn CDI = 1.16×10−5 mg/kg-day and HQ = 3.86×10−5 (RfD = 0.3 mg/kg-day).

Table 4: Empirical Monte Carlo uncertainty summary for Zn (10,000 iterations).

Metal	Csoil (mg/kg)	IR (kg/day)	ED (years)	EF (days/year)	BW (kg)	AT (days)	CDI (mg/kg-day)	RfD (mg/kg-day)	HQ
Zn	8.46	1.0×10−4	20	350	70	7,300	1.16×10−5	0.3	3.86×10−5

Endpoint	**P5**	**P50**	**P95**	**Maximum / threshold**
76+8	7.10	8.20	9.85	9.85
Zn CDI (mg/kg-day)	9.73×10−6	1.12×10−5	1.35×10−5	1.35×10−5
Zn HQ	3.24×10−5	3.74×10−5	4.50×10−5	HQ > 1: 0/10,000

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401

402 The Monte Carlo analysis shows that the Zn HQ remained several orders of magnitude below
403 the screening threshold of 1 across all 10,000 iterations. Because the simulation resampled only
404 the five observed concentrations and held exposure parameters fixed, the result should be
405 interpreted as an empirical uncertainty analysis of the available dataset rather than as a
406 prediction of all future site conditions.

407 The risk results should therefore be used to prioritize continued monitoring rather than to infer
408 specific contaminant sources or natural attenuation. Future studies should increase the number
409 of independent samples and include validated detection limits, deeper soil, groundwater, and
410 repeated temporal measurements.

411 The Monte Carlo histogram in Figure 4 summarizes the simulated Zn HQ distribution.

412 **3.5. Phytoremediation Potential of Indigenous Flora**

413 Vegetation was observed at the site, including Chrysopogon zizanoides, Bauhinia variegata,
414 Conocarpus erectus and Prosopis juliflora. Their phytoremediation relevance is discussed as
415 literature-supported potential only. Plant root and shoot tissues were not analysed; therefore,

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site-specific metal uptake, phytoextraction, phytostabilization, BCF and TF were not demonstrated.

Table 5: Indigenous plants found at Mehmood Boot Landfill and its phytoremediation potential

Scientific name	Common name	Family	Height	Literature-supported phytoremediation potential
Chrysopogon zizanoides L. 	Vetiver grass	Poaceae	5 feet	Literature reports potential metal tolerance/uptake and stabilization; site-specific uptake was not measured in this study (Wasino et al., 2019).
Bauhinia variegata 	Orchid tree	Fabaceae	15 feet	Literature-supported potential for metal stabilization; site-specific metal uptake was not measured (Memon & Schröder, 2009).
Conocarpus erectus 	Buttonwood	Combretaceae	6 feet	Potential for metal tolerance and soil stabilization reported in the literature; site-specific uptake was not measured.
Prosopis juliflora 	Mesquite	Fabaceae	3 feet	Literature-supported potential for metal uptake/tolerance; actual site-specific phytoextraction or phytostabilization was not demonstrated.

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The available soil measurements indicate low concentrations relative to the selected regulatory screening values, with zinc having the highest measured mean concentration. A validated numerical PERI is not reported because a defensible geochemical background dataset was not available. Likewise, natural attenuation cannot be established from a single sampling event.

In the current study, tissue analysis of plants was not conducted; therefore, bioconcentration factor (BCF) and translocation factor (TF) concentrations could not be evaluated. The potential of phytoremediation to be discussed herein is rooted in the observation of plants in the study area and their natural colonization at disposal areas, as well as literature-based evidence associated with the metal tolerance and acquisition ability of the identified plant species. The phytoremediation assessment therefore remains qualitative, and no conclusion on site-specific metal uptake can be drawn without tissue-level metal quantification. Systematic studies need to be included in the future, BCF and TF values by plant sampling and laboratory analysis to identify the values, thus, facilitating a stricter and location-based test of metal uptake and translocation efficiency

This study assessed heavy-metal contamination and associated screening-level ecological and human-health risks in post-closure near-surface soils at the Mehmood Booti landfill, Lahore. Five independent soil samples were collected from 30–90 cm depth. Zinc had the highest reported mean concentration (8.46 ± 1.11 mg/kg), while Cd was below the reporting limit. The reported Cr and Pb readings were below the stated method detection limits and therefore require cautious interpretation rather than treatment as fully quantified concentrations. The measured Zn concentration was below the selected PEQS screening value.

For human-health screening, the corrected adult soil-ingestion calculation for Zn produced CDI = $1.16 \times 10{-}5$ mg/kg-day and HQ = $3.86 \times 10{-}5$. The 10,000-iteration empirical Monte Carlo analysis, based only on the five observed Zn concentrations, produced Zn CDI values of P5 =

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9.73 × 10−6, P50 = 1.12 × 10−5, and P95 = 1.35 × 10−5 mg/kg-day, while Zn HQ values were P5 = 3.24 × 10−5, P50 = 3.74 × 10−5, and P95 = 4.50 × 10−5. No simulated HQ exceeded 1. A validated numerical PERI was not reported because an appropriate geochemical background dataset was unavailable. Inferential ANOVA/t-test p-values were not reported because the available five-sample dataset lacks independent replicate groups. These decisions avoid pseudoreplication and unsupported numerical claims.

3.6. Scope and Limitations of the Study

These results are limited to the scope and limitations of this study. The assessment is based on a few samples (n = 5) taken at one sampling time from the near surface layer (30-90 cm). The sampling density is representative of site-access and safety issues common in post-closure landfill studies, and similar screening-level assessments reported in this manuscript. This small sample size reduces the statistical power of the analysis, and the generalizability of the results to the entire site of the landfill; the descriptive statistics and empirical Monte Carlo analysis resampled only the five observed concentrations and should be interpreted accordingly. Future work recommendations involve expanding the sampling campaign to a greater number of independent samples, multiple soil depths, and repeated sampling over time. The risk assessment is screening level and only considers the adult soil-ingestion pathway for the four metals analysed (chromium, cadmium, lead and zinc) and excludes dermal contact, inhalation, child exposure, deeper soil, groundwater and leachate. The seasonality and trends were not evaluated due to the fact that only one sampling event was conducted. Furthermore, there was no measurement of metal concentration in the plant tissues, and thus the discussion on phytoremediation is qualitative.

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4. Conclusions

This study assessed heavy-metal contamination and associated ecological and human-health risks in post-closure near-surface soils at the Mehmood Booti landfill, Lahore. Concentrations of chromium, cadmium, lead, and zinc were generally below applicable Punjab Environmental Quality Standards and relevant guideline limits, with zinc showing the comparatively highest concentration (8.46 ± 1.11 mg/kg) but remaining below regulatory thresholds. The ecological risk assessment indicated a negligible overall risk (potential ecological risk index = 0.0297), while hazard quotient and hazard index estimates indicated no substantial non-carcinogenic health risk under the assessed exposure assumptions. Monte Carlo uncertainty analysis further indicated that estimated risks may vary with contaminant concentrations and exposure parameters. Therefore, the findings are limited to the sampled near-surface soils and should not be interpreted as evidence of whole-landfill or groundwater safety. Future studies should incorporate larger sample sizes, multiple soil depths, repeated temporal sampling, groundwater and leachate monitoring, and plant-tissue analysis to better evaluate long-term contaminant behaviour and the actual phytoremediation potential of indigenous vegetation.

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Data availability

Data presented in current research work are available on request.

Conflicts of interest

The authors declare no conflict of interest.

4. References

Alam, A., Chaudhry, M. N., Ahmad, S. R., Batool, A., Mahmood, A., & Al-Ghamdi, H. A. (2021). Application of EASEWASTE model for assessing environmental impacts from solid waste landfilling. *Archives of Environmental Protection*, *47*(4), 84–92. https://doi.org/10.24425/aep.2021.139504

Alam, A., Chaudhry, M. N., Mahmood, A., Ahmad, S. R., & Butt, T. E. (2021). Development and application of conceptual framework model (CFM) for environmental risk assessment of contaminated lands. *Saudi Journal of Biological Sciences*, *28*(11), 6167–6177. https://doi.org/10.1016/j.sjbs.2021.06.069

Alam, A., Tabinda, A. B., Qadir, A., Butt, T. E., & Mehmood, A. (2017). Ecological risk assessment of an open dumping site at Mehmood Booti Lahore, Pakistan. *Environmental Science and Pollution Research*, *24*(21), 17889–17899.

El-Beltagi, H. S., & Mohamed, A. A. (2010). Changes in non-protein thiols, antioxidant enzyme activity and ultrastructural alteration in radish plant (Raphanus sativus L.) grown under lead toxicity. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *38*(3), 76–85.

IRIS, I. R. I. S. (2019). *Basic information about the Integrated Risk Information System*. U.S. Environmental Protection Agency.

ACCEPTED MANUSCRIPT

ISPRA. (2013). *Urban waste report*. Italian Institute for Environmental Protection and Research.

Jadoon, I., Ahmad, K., Nazir, A., Khan, S. A., Ismail, A. M., Matar, A., Alharbi, A. S., & Saleh, H. A. F. (2025). Health risk assessment and levels of heavy metals contaminated drinking water used by both adults and children from Nawanshahr town. *Global NEST Journal*, *27*(4).

Khan, M., Ahmad, M., Sultan, M., Sohoo, I., Ghimire, P., Zahid, A., Sarwar, A., Farooq, M., Sajjad, U., Abdeshahian, P., & Yousaf, M. (2021). Biogas Production Potential from Livestock Manure in Pakistan. *Sustainability*, *13*. https://doi.org/10.3390/su13126751

Komal, N., Zaman, Q. uz, Pantera, A., Yasin, G., Ashraf, K., Nazir, S., & Baig, M. B. (2024). *Climate-Smart Agriculture: Potential Role in Carbon Sequestration and to Address Climate Change Under Irrigated Agro-Ecosystems BT - Climate-Smart and Resilient Food Systems and Security* (M. Behnassi, A. A. Al-Shaikh, R. Hussain Qureshi, M. Barjees Baig, & T. K. A. Faraj, Eds.; pp. 73–110). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-65968-3_4

Maqsoom, A., Aslam, B., Hassan, U., Kazmi, Z. A., Sodangi, M., Tufail, R. F., & Farooq, D. (2020). Geospatial assessment of soil erosion intensity and sediment yield using the revised universal soil loss equation (RUSLE) model. *ISPRS International Journal of Geo-Information*, *9*(6), 356.

Mary, R., Nasir, R., Alam, A., Tariq, A., Nawaz, R., Javied, S., & Khan, S. N. (2023). Exploring hazard quotient, cancer risk, and health risks of toxic metals of the Mehmood Booti and Lakhodair landfill groundwaters, Pakistan. *Environmental Nanotechnology, Monitoring & Management*, *20*, 100838.

Mohamed, A. A., El-Beltagi, H. S., & Rashed, M. M. (2009). Cadmium stress induced change

ACCEPTED MANUSCRIPT

in some hydrolytic enzymes, free radical formation and ultrastructural disorders in radish plant. *Electronic Journal of Environmental, Agricultural and Food Chemistry*, *8*, 969–979.

Muneer, M., Kong, D., Wan, R., Liu, X., Song, Q., & Rahman, M. U. (2026). Experimental and coupling analysis of municipal solid waste (MSW) shear strength under multiple influencing parameters. *PLOS ONE*, *21*(3), e0344191. https://doi.org/10.1371/journal.pone.0344191

Okoye, H. O. (2023). Human health risks of metal contamination in shallow wells around waste dumpsites in Abeokuta metropolis, southwestern Nigeria. *Environmental Monitoring and Assessment*, *195*(7), 881.

Pakar, N. A., Redeker, K., & Munis, M. F. H. (2025). Spatiotemporal patterns of pesticide residues in intensive agricultural soil and water bodies in Shaheed Benazirabad, Pakistan. *Environmental Monitoring and Assessment*, *197*, 427. https://doi.org/10.1007/s10661-025-13873-2

Rafique, F., Nazir, A., Khan, S. A., Abbasi, A. M., Ismail, A. M., Darrag, H. M., Yehia, R., & Hajjar, M. J. (2025). Effects of Cd and Cr stress on physiological and morphological traits of two cultivars of wheat (Triticum aestivum L.) under hydroponic system. *Global NEST Journal*, *27*(3).

Romeh, A. A., & Ismail, A. M. (2026). Sustainable utilization of Pistia stratiotes for phytoremediation of heavy metals and nutrients contaminated drainage water. *International Journal of Phytoremediation*, 1–14.

Smol, M., Kulczycka, J., Lelek, Ł., Gorazda, K., & Wzorek, Z. (2020). Life cycle assessment (LCA) of the integrated technology for phosphorus recovery from sewage sludge ash (SSA) and fertilizers production. *Archives of Environmental Protection*, *46*(2), 42–52.

ACCEPTED MANUSCRIPT

564 Vongdala, N., Tran, H. D., Xuan, T. D., Teschke, R., & Khanh, T. D. (2019). Heavy metal
565 accumulation in water, soil and plants of municipal solid waste landfill in Vientiane, Laos.
566 *International Journal of Environmental Research and Public Health*, *16*(1), 1–13.

567 Zheng, K., Lv, B., Wu, L., Wang, C., Xu, H., Li, X., Wu, Z., Zhao, Y., & Zheng, Z. (2022).
568 Protecting effect of emodin in experimental autoimmune encephalomyelitis mice by
569 inhibiting microglia activation and inflammation via Myd88/PI3K/Akt/NF-κB signalling
570 pathway. *Bioengineered*, *13*(4), 9322–9344.
571 https://doi.org/10.1080/21655979.2022.2052671

572

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