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Seasonal Dynamics in Heavy Metal Pollution and Environmental Risk in Surface Soils Near a Battery Recycling Plant in Ogijo, Southwestern Nigeria

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ABSTRACT

The study assessed seasonal variations in heavy metal pollution and ecological risk in surface soils around a spent-battery recycling plant in Ogijo, south-western Nigeria. Forty topsoil samples (0–15 cm) were collected for two seasons and analyzed for Mn, Fe, Cu, Zn, Pb, Co, Cd, Cr and Ni using Atomic Absorption Spectrophotometry. Contamination factor, geoaccumulation index, enrichment factor and ecological risk index were calculated. The standard toxic-response factors and correlations were used to identify common sources. Most heavy metals (Cu, Zn, Pb, Cr, Ni) occurred below their soil background levels, whereas Cd was greatly elevated in both seasons (16.69mg/kg wet; 6.24mg/kg dry vs 0.3mg/kg background), and Co was moderately enriched in the dry season. Wet-season indices classified Cd as extremely polluted (CF = 55.6; IGEO > 5), with EF many orders of magnitude above unity and ERI ≈ 1669, while other metals had CF < 1 and ERI < 5, indicating low risk. In the dry season, Cd remained the dominant pollutant (CF = 20.8; ERI ≈ 624) and Co showed CF slightly above 1, but all other metals stayed within the low-risk range. Correlation matrices revealed strong, significant associations among Cu, Zn, Ni, Cd, Fe and Pb in the wet season, consistent with a common anthropogenic source and hydrological mixing, whereas dry-season correlations were weaker and more heterogeneous. Overall, soils near the facility are ecotoxicologically dominated by Cd, particularly in the wet season, indicating the need for stricter control of recycling activities, targeted remediation and continuous monitoring.

Keywords:
Battery Recycling,
Ecological risk,
Heavy metals,
Seasonal Dynamics,
Soil pollution.

INTRODUCTION

Another contemporary issue in the environment of the modern day is soil heavy metal pollution especially in regions where the batteries are being recycled and other related businesses. These places are prone to be contaminated more because the toxic heavy metals continuously flow into the soil and other places through bad waste and wastewater disposal. The common contaminants that have been widely reported are chromium (Cr), lead (Pb), zinc (Zn), manganese (Mn), and cadmium (Cd). Such metals are bioaccumulated in living organisms and pose long-term risks to soil and water as well as human health since they are not washed away (Awoyemi A.R 2024; Popoola *et al.,* 2019). The anthropogenic activities, including uncontrolled industrial effluents and inadequate waste management activities worsen the state of heavy metal contamination of soils. The contamination of this type is a big threat especially in the battery recycling plants where mishandling of hazardous chemicals takes place frequently. With regard to the level of soil pollution in Nigerian and other urban and industrial areas of the developing world, researchers have found that the areas had developed as a result of unregulated informal economic sectors (Iwegbue *et al.,* 2009; Okorie *et al.,* 2012). High levels of metal are, especially, detrimental to the soil microbes, which are crucial in the digestion of organic matter and the cycling of nutrients. The disturbances in the microbial populations can influence soil fertility and ecological health (Giller *et al.,* 2009; Chibuike & Obiora, 2014). Ubiogor & Adeyemo (2017) and Popoola *et al*. (2019) have demonstrated that seasonal variation may influence the distribution and behavior of heavy metals in the soil. The contamination is more localized in the dry season, which would imply that the industrial inputs are present, unlike in the wet season where the erosion and runoff diffuses the contamination spread to more areas. The exposure routes are also increased when the contaminated soils are washed by the adjacent groundwater systems, and that is where the agricultural irrigation systems and the drinking water sources are at risk (Akan *et al.,* 2010; Wuana & Okieimen, 2011).

The cumulative exposure to low doses of numerous heavy metals via soil, water, and food poses a serious yet under-recognized public health danger, especially in low-income populations living near industrial zones (Jarup, 2003). Exposure to lead has been related to neurological and developmental abnormalities, cadmium to kidney damage and bone illness (Matta & Gjyli, 2016; Hassan *et al.,* 2020). Mehrpour (2012) & Genchi *et al*. (2020) reported that manganese and chromium disrupt metabolic and biological processes, resulting in respiratory and neurological disease.

Long-term exposure to such pollutants has also been related to immunosuppressive effects and endocrine disruption, especially in infants and pregnant women, rendering these groups more susceptible (Jaishankar *et al.,* 2014; Tchounwou *et al.,* 2012). Flora *et al*. (2008) revealed links between chronic exposure to heavy metals including nickel and cobalt, and cardiovascular abnormalities, oxidative stress, and mitochondrial dysfunctions (Wang & Fowler, 2008).

Effective monitoring and cleanup techniques at battery recycling factories to reduce heavy metal pollution in their communities is of great concern. Inadequately executed operations in most informal facilities where basic technical controls such as liners and leachate collecting systems greatly contribute to the leaching and concentration of heavy metals in soils, causing damage to human health and the environment (Singh *et al.,* 2011).

Phytoremediation, a cost-effective and ecologically benign technique employing metal-accumulating plants, has been presented as a viable remediation method, but its implementation remains restricted in underdeveloped countries owing to regulatory gaps and low knowledge (Ali *et al.,* 2013).

The causes, the pathways and effects of the heavy metals should be undergoing significant research due to the lack of easy understanding to the metals due to their toxicity and persistence. It is because the greater potentials of geostatistical modelling, remote sensing, and geographic information systems have contributed to the possibility to identify particular areas of contamination more precisely and forecast the trends of contamination further in the future (Li, *et al.,* 2020). Nevertheless, in the areas like battery recycling industry in which informal action is the most prevalent, there is no data capturing.

Heavy metals in the soil are still bad for the ecosystem and people's health in regions where batteries are recycled without permission. Recycling at Ogijo, Southwestern Nigeria, introduced harmful metals including cadmium, lead, chromium, nickel, and copper into the soil surrounding them. These contaminants persist in the environment, accumulate in living things, and cause ecosystems, groundwater, farming, and people's health at risk. Not much is known about how these metals work in the soil around battery recycling plants, how they influence the ecosystem, or where they come from. Despite the fact that there is proof of heavy metal contamination in other parts of Nigeria that are industrial. This study addresses the gap by examining the concentrations of heavy metals, their seasonal variations, pollution indices, and ecological risks at a battery recycling facility in Ogijo.

The specialists in the field of public health, environmental science and toxicology must work together to find effective solutions. In an effort to answer the research question, what are the environmental behavior and health effects of heavy metal pollution in the soils of a battery recycling facility? This study tried to determine the extent of heavy metals, how they change with seasons how they relate with other contamination causes, geo-accumulation, and eco-factors. These concerns should be addressed and proper laws and long-term waste management policies should be incorporated in order to reduce the risk of heavy metal.

MATERIALS AND METHODS

Study area

The study was conducted around a spent battery-recycling facility in Ogijo, Ogun State, southwestern Nigeria, which has a tropical climate with distinct wet and dry seasons. The site lies within latitude 6°50′54.60″ N and longitude 3°38′46.79″ E and is surrounded by residential and agricultural land, (Figure 1).

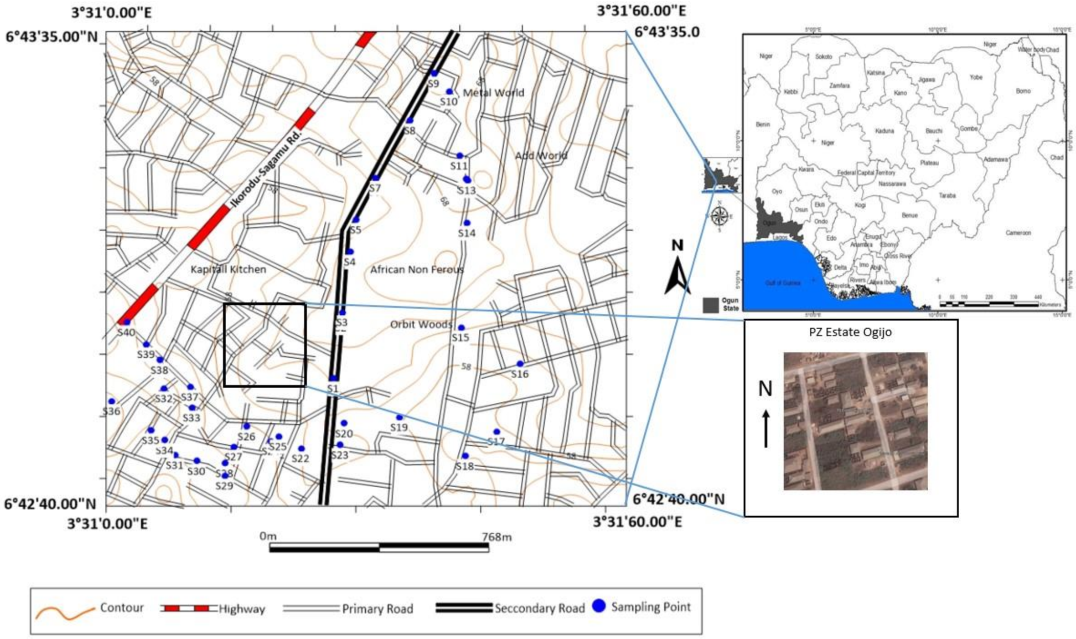

Figure 1: The study sites are marked on the map of Nigeria

Soil sampling and preparation

A total of 80 surface soil samples (0–15 cm) were collected, comprising 40 samples in the wet season and 40 in the dry season. Sampling locations were laid out on a regular grid at 5–10 m intervals around the facility. At each grid point, the exact sampling spot was chosen by a random offset (<1 m) to reduce spatial bias. Three subsamples within a 1 m² area were combined to form one composite sample, capturing local variability while maintaining statistical independence among sites. Surface debris was removed before sampling using a plastic trowel. Samples were placed in clean, labelled polyethylene bags, transported to the laboratory, air-dried, gently disaggregated, and sieved to <2 mm prior to digestion, according to Baker *et al*. (2006).

Acid digestion and metal determination

Soil samples were digested following Ohimain *et al.* (2012). For each sample, 1.0 g of dried, 2 mm soil was weighed into a 100 mL beaker and mixed with 0.5 mL concentrated H_2SO_4, 1.0 mL $HClO_4$ and 5.0 mL HNO_3. The mixture was heated on a hotplate at 120–140 °C until near dryness (fuming stage), allowed to cool, then quantitatively transferred to a 25 mL volumetric flask and made up to volume with deionized water. A reagent blank and a certified reference soil were processed with each digestion batch. Concentrations of Mn, Fe, Cu, Zn, Pb, Co, Cd, Cr and Ni were determined using a flame atomic absorption spectrophotometer (FAAS, PG-990).

Instrument calibration was checked with multi-element standards. Accuracy was verified using certified reference soil with recoveries between 90 and 110 %. Duplicate digestions and analyses (10 % of samples) yielded coefficients of variation <5 % for all metals, indicating good analytical precision.

Statistical analysis

Descriptive statistics (mean, standard deviation, coefficient of variation) were computed for each metal and season. Seasonal differences between wet and dry concentrations were tested using independent-samples t-tests; when normality or homoscedasticity assumptions were not met, the Mann–Whitney U test was applied. A significance level of $p<0.05$ was adopted. Pearson correlation analysis was carried out separately for each season to examine inter-metal relationships and potential common sources.

Methods

Contamination factor (CF)

The CF metric has also been extensively applied to monitor the environment and offers a strong platform to monitor soil and sediment pollution by heavy metals as discussed by Tokatli *et al.,* (2023).

$$CF = \frac{Ci}{Cbg} \qquad (1)$$

Where CF is the factor of contamination, Ci: is the concentration of the metal in the soil or sediment measured. C_{bg} refers to the background level of the metal in the pure soil or sediments.

Geoaccumulation Index (IGEO)

This was formulated by Muller (1969) and is very popular in the determination of the level of pollution and health conditions of the sediment as stated by equation 2. The outcome can be interpreted by the public and the regulation bodies with ease (Islam *et al*, 2018)

$$Igeo = log_2\left(\frac{C_n}{1.5B_n}\right) \qquad (2)$$

Where C_n is the measured concentration of the metal in the sample

B_n is the background concentration of the metal in a reference material

Factor 1.5 accounts for natural variation in background levels due to lithogenic effect.

Pollution load index (PLI)

This is an index to assess the degree of contamination in soils and/or sediment and calculated as the n^th^ root of the number of multiplied CF values based on equation 3

$$PLI = (Cf1 \,.\, Cf2 \ldots\ldots\ldots. Cfn)^{1/n} \qquad (3)$$

Where: CF_1, CF_2 ,…, CF_n are contamination factors of individual metals while n is the number of metals assessed (Haris, *et al.,* 2017).

Enrichment Factor (EF)

The Enrichment Factor is used to evaluate the degree of anthropogenic impact on metal concentrations relative to natural levels. EF was calculated using the following formula:

$$EF = \left(\frac{C_{metal}}{C_{Fe}}\right) \times \left(\frac{B_{metal}}{B_{Fe}}\right) \qquad (4)$$

Where C_n is the concentration of the target metal in the sample, B_n are the background concentrations of the target and reference elements, respectively.

An EF > 1.5 indicates significant anthropogenic enrichment (Sutherland, 2000; Yongming *et al.,* 2006

Ecological Risk Factor (ERI)

The ecological risk factor, introduced by Hakanson (1980), quantifies the potential ecological threat posed by individual heavy metals. It is calculated as:

$$ERI = CF \times Tr \qquad (5)$$

Where Tr_i is the toxic response factor for metal (e.g., Cd = 30, Pb = 5, Cu = 5, Zn = 1, Cr = 2, Ni = 5), and C_f is the contamination factor:

This formula reflects both the concentration of the contaminant and its relative toxicity.

Risk Index (RI)

To determine the overall ecological threat posed by the combined presence of multiple metals, the Risk Index (RI) was calculated by summing the individual ecological risk factors:

$$RI = \sum Eri \qquad (6)$$

RI provides a cumulative estimate of potential ecological harm from the suite of metals under study (Hakanson, 1980).

Soil guidelines ranges were extracted from Kabata-Pendias (2011).

The summary of the equations adopted for method on pollution and ecological risk indices is as well shown in the (Table 1) for clarity;

Table 1: Summary of Pollution and Ecological Risk Indices

Index	Purpose	Equation	Variables and Definitions	Key References
Contamination Factor (CF)	Assesses the level of metal contamination relative to background values in soil or sediment	CF = Ci / Cbg	CF: contamination factor Ci: measured concentration of metal in soil or sediment Cbg: background concentration of metal in uncontaminated soil or sediment	Tokatli et al. (2023)
Geoaccumulation Index (Igeo)	Determines pollution intensity by comparing current metal concentrations with pre-industrial levels	Igeo = $\log_2$ (Cn / (1.5 × Bn))	Cn: measured concentration of metal in sample Bn: background concentration of metal 1.5: correction factor for natural lithogenic variation	Muller (1969); Islam et al. (2018)
Pollution Load Index (PLI)	Evaluates overall pollution status of soils or sediments from multiple metals	PLI = (CF_1 × CF_2 × … × CFn)$^{1/n}$	CF_1–CFn: contamination factors of individual metals n: number of metals assessed	Haris et al. (2017)
Enrichment Factor (EF)	Identifies anthropogenic influence on metal concentrations	EF = (Cmetal / CFe) × (Bmetal / BFe)	Cmetal: concentration of target metal in sample CFe: concentration of reference element (Fe) in sample Bmetal: background concentration of	Sutherland (2000); Yongming et al. (2006)

			target metal BFe: background concentration of reference element	
Ecological Risk Factor (ERI)	Quantifies potential ecological risk posed by individual metals	ERI = CF × Tr	CF: contamination factor Tr: toxic response factor (e.g., Cd = 30, Pb = 5, Cu = 5, Zn = 1, Cr = 2, Ni = 5)	Hakanson (1980)
Risk Index (RI)	Estimates cumulative ecological risk from multiple metals	RI = ΣERI	ERI: ecological risk factor of each metal	Hakanson (1980)

Table 2: Guideline/background concentration ranges for selected metals in soils used as reference values in contamination and ecological risk assessment (Kabata-Pendias, 2011)

Metal	Guideline Range (mg/kg)	Typical Soil Background Description
Manganese (Mn)	300–1,000	Natural background levels in mineral soils
Iron (Fe)	20,000–50,000	Major soil element (background concentration)
Copper (Cu)	5–50	Background concentrations in surface soils
Zinc (Zn)	20–200	Typical background range in soils
Lead (Pb)	10–70	Natural soil background values
Cobalt (Co)	1–40	Background levels depending on parent material
Cadmium (Cd)	0.1–1.0	Trace background concentration in soils
Chromium (Cr)	10–100	Natural background in most soil types
Nickel (Ni)	5–50	Background concentration in uncontaminated soils

RESULTS AND DISCUSSION

Comparative analysis of heavy metal concentrations in wet and dry soil samples

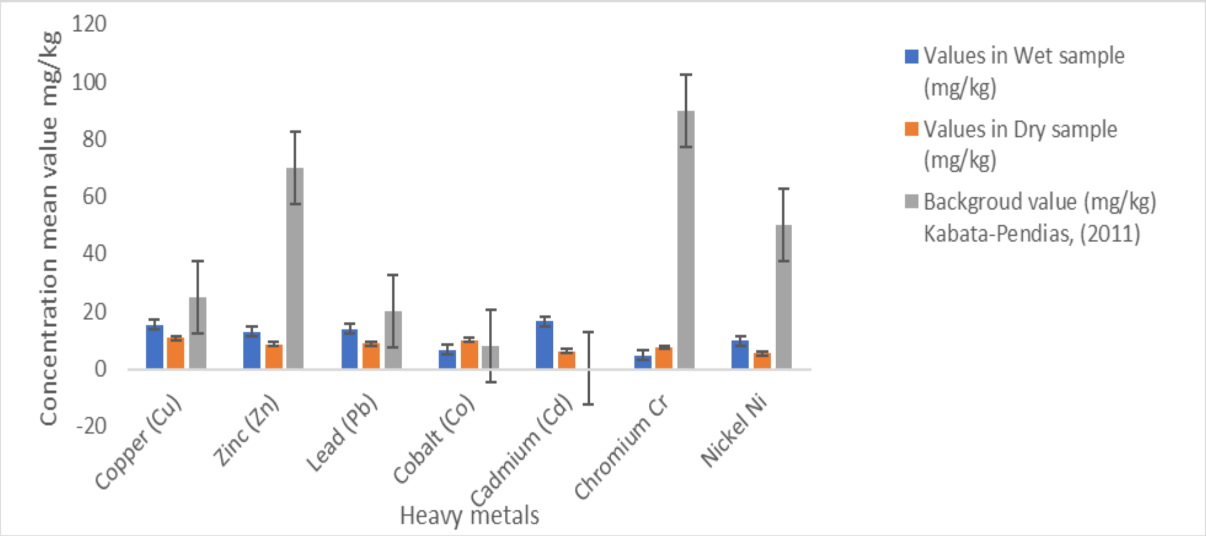

Figure 2: Mean concentration of heavy metals (mg/kg)

The bar chart in Figure 2 compares mean concentrations of Cu, Zn, Pb, Co, Cd, Cr and Ni in wet and dry soil samples from the battery-recycling site with soil background values reported by Kabata-Pendias (2011). This side-by-side view allows assessment of both seasonal variability and deviation from typical trace-element levels in uncontaminated soils. For most metals (Cu, Zn, Pb, Cr, Ni), both wet and dry-season concentrations remain below the corresponding background values, indicating low to moderate contamination relative to natural soils, even though their presence is clearly linked to anthropogenic inputs from battery components and associated wastes. In contrast, Cd and, to a lesser extent Co in the dry season, markedly exceed their background values, identifying them as the principal indicators of contamination at the site. Mean Cd concentrations exceeded the guideline values (Table 2), indicating potential anthropogenic input.

Cadmium shows the most critical enrichment, with mean concentrations of 16.687 mg/kg (wet) and 6.238 mg/kg (dry) compared with a background value of 0.3 mg/kg. This corresponds to orders-of-magnitude elevation and corroborates the very high contamination factors, IGEO values and ecological risk indices calculated for Cd. Such levels are of particular concern because Cd is highly mobile in soils, readily taken up by plants and known to bioaccumulate in food chains, posing risks to human health through consumption of contaminated crops and exposure to contaminated dust. Similar patterns of elevated Cd in soils affected by industrial activities and waste disposal have been documented in other studies, which highlight the long-term persistence and bioaccumulative nature of Cd in contaminated environments (Ogundiran & Osibanjo, 2009; Nabulo *et al*., 2006; Kabata-Pendias, 2011).

Lead, copper and zinc occur at concentrations below their background values 20.0, 25.0, and 70.0 respectively, but still reflect clear anthropogenic influence. Wet-season Pb (13.861 mg/kg) and Cu (15.457 mg/kg) are higher than their dry-season counterparts (8.887 and 10.703 mg/kg, respectively), consistent with enhanced mobilization during the rainy season, likely from battery plates, casings and associated metallic scraps. Although these values do not exceed generic soil background thresholds, Pb and Cu are toxic and persistent, and their co-occurrence with Cd in soils impacted by battery handling has been widely reported in Nigeria and elsewhere, indicating contamination pathways associated with informal recycling and inadequate waste management (Ogundiran & Osibanjo, 2009). Zn shows wet- and dry-season concentrations (13.078 and 8.742 mg/kg) well below its background of 70 mg/kg, yet elevated Zn can still affect soil microbial activity and plant growth if local hotspots occur, so continued monitoring remains warranted.

Their behavior contrasts sharply with that of Cd and Co, emphasizing the anthropogenic character of the latter metals. Cobalt occurs at 6.728 mg/kg (wet) and 10.056 mg/kg (dry) relative to a background of 8 mg/kg, indicating slight sub-background levels in the wet season and moderate enrichment in the dry season. Although Co concentrations are much lower than those of the major base metals, the dry-season enrichment suggests that Co contributes measurably to the site's overall metal burden and may originate from specific battery components or associated alloys.

Chromium and nickel exhibit wet-season and dry-season concentrations below their respective backgrounds (Cr 4.674–7.543 mg/kg vs 90 mg/kg; Ni 5.555–9.729 mg/kg vs 50.0 mg/kg), suggesting that they are not strongly elevated in a bulk sense, though their presence is still consistent with leakage from battery electrodes and other metallic wastes. Both Cr and Ni are recognized for their potential carcinogenicity and environmental persistence, so even moderate levels add to cumulative risk, particularly in combination with higher-risk elements such as Cd and Pb. The relatively low average values therefore do not preclude the existence of more contaminated micro-sites, especially near active dumping or burning areas.

Seasonally, the values shows that most metals (Cu, Zn, Pb, Co, Cd, Ni) have higher mean concentrations in the wet season than in the dry season, this pattern indicates that rainfall and surface runoff play a key role in mobilizing and redistributing metals from discarded batteries and associated wastes into surrounding soils. Wet-season peaks, especially for Cd, point to heightened ecological and potential human-health risk during and shortly after the rains, when metals are more mobile, more bioavailable and more likely to be transported into adjacent agricultural land or water bodies. In contrast, the dry season is characterized by somewhat lower concentrations but an increased risk of dust resuspension and inhalation exposure.

Generally, the data values support a contamination scenario dominated ecotoxicologically by cadmium, with Co, Pb and Cu as additional anthropogenic markers, and Zn, Cr and Ni contributing at lower levels. The strong contrast between Cd concentrations and their very low background value underscores the severity of contamination at the battery-recycling site and the need for targeted risk management, including improved waste handling, containment of contaminated soils, and regular monitoring. These observations are consistent with the broader literature on heavy-metal pollution around informal and poorly regulated recycling facilities in low- and middle-income countries, where inadequate environmental controls frequently result in elevated soil metal burdens and associated health risks for nearby communities (Ogundiran & Osibanjo, 2009; Nabulo *et al*., 2006; Kabata-Pendias, 2011).

Correlation analysis of heavy metals in soil from a spent battery recycling site (Wet season)

Table 3, shows the correlation matrix of heavy metals in the soil samples from the spent battery recycling site. This offers crucial insight into the relationships among contaminants and their likely sources. The Pearson correlation coefficients show that there are strong positive relationships between Cu, Zn, Ni, Cd, Fe and Pb with values ranging between 0.82 to 0.94 indicating that these metals must be co-contaminants brought about by a common anthropogenic source, most probably by battery components (anodes, casings, or electrodes) which is supported by the finding of Ogundiran & Osibanjo (2009) who have shown that in many cases, the pattern of multi-metal pollution is observed at an informal battery recycling.

Table 3: Correlation of heavy metal in soil (wet season)

Heavy metals (ppm)	Mn	Cu	Zn	Ni	Cd	Fe	Pb	Cr	Co
Mn	1								
Cu	0.80598	1							
Zn	0.84547	0.87750	1						
Ni	0.76959	0.81894	0.93704	1					
Cd	0.53442	0.62442	0.66045	0.74093	1				
Fe	0.51005	0.70726	0.58881	0.66390	0.77593	1			
Pb	0.42343	0.66082	0.56490	0.62771	0.58886	0.76109	1		
Cr	0.33664	0.42557	0.39855	0.39133	0.44997	0.33134	0.25192	1	
Co	0.36150	0.48550	0.40345	0.47063	0.60907	0.86958	0.74125	0.27431	1

The correlation analysis revealed marked seasonal differences in the co-behavior of heavy metals in soils around the battery recycling site, with a much stronger and more coherent multi-metal pattern in the wet season than in the dry season.

Wet season correlation structure

During the wet season (Table 3), Pearson correlation coefficients among most metals were strong and positive, indicating that they tend to increase and decrease together and are likely controlled by common anthropogenic sources and hydrological processes. Using the available raw datasets, the number of observations per metal is n = 40, so correlation coefficients with $|r|\gtrsim 0.31$ are statistically significant at $p<0.05$, and $|r|\gtrsim 0.40$ at $p<0.01$.

A tightly linked cluster was observed among Cu, Zn and Ni, with very high correlation coefficients (Cu–Zn r=0.8775, Zn–Ni r=0.9370, Cu–Ni r=0.8189; all $p\ll 0.01$), showing that these metals share closely similar spatial distributions. This pattern is characteristic of co-contamination from common anthropogenic sources such as battery casings, electrodes and associated metallic components, and is consistent with previous findings in soils impacted by battery handling and hazardous waste disposal. Cadmium also showed strong positive relationships with Ni, Zn and Cu (Cd–Ni r=0.7409, Cd–Zn r=0.6605, Cd Cu r=0.6244; p≪0.01), indicating that areas enriched in base metals are also disproportionately affected by Cd, reinforcing its identification as a key contaminant associated with informal recycling activities. Iron and cobalt formed another closely associated sub-group, with Fe–Co r=0.8696r=0.8696 and strong correlations of Fe with Cd (r = 0.7759), Pb (r = 0.7611) and Cu (r = 0.7073), and of Co with Pb (r = 0.7413) and Cd (r = 0.6091) (all p≪0.01). Although Fe and Mn are largely geogenic, their strong correlations with clearly anthropogenic metals (Cd, Pb, Cu, Co) suggest that they participate in the same contamination plume, either through co-release from metal-rich wastes or through adsorption and co-transport on the same soil phases. Manganese was also positively correlated with Zn, Cu and Ni (r = 0.8455, 0.8060 and 0.7696, respectively; p≪0.01), further supporting its involvement in the multi-metal contamination pattern despite its natural background role.

In contrast, chromium exhibited only moderate correlations with most metals (e.g., Cr-Zn r=0.3986, Cr–Cd r=0.4500, Cr–Cu r=0.4256, Cr Pb r=0.2519), some of which are only marginally above typical significance thresholds. This weaker connectivity suggests that Cr may partly originate from distinct sources (other industrial inputs or geogenic background) and may follow slightly different geochemical pathways than the strongly co-varying metals. Overall, the wet season matrix indicates a highly coherent multi-metal contamination pattern dominated by anthropogenic inputs, intensively mobilized and redistributed by rainfall-driven runoff and leaching.

Correlation analysis of heavy metals in soil from a spent battery recycling site (Dry season)

Unlike the wet season where most heavy metals exhibited substantial inter-correlations, the Pearson coefficient during the dry season revealed weaker and more distributed relationships among the metals.

Table 4: Correlation of heavy metal in soil (dry season)

Heavy metal (ppm)	Fe	Mn	Cu	Zn	Ni	Cd	Pb	Cr	Co
Fe	1								
Mn	0.37024	1							
Cu	0.29558	0.20989	1						
Zn	0.04327	0.37337	0.17598	1					
Ni	-0.10930	0.16339	0.27625	0.49726	1				
Cd	0.03121	0.34044	0.01749	0.47418	0.39139	1			
Pb	0.17056	-0.13100	0.46261	0.20757	0.05821	0.03618	1		
Cr	-0.11100	0.21841	0.10607	0.59654	0.12273	0.37931	0.31921	1	
Co	0.07583	0.35411	0.32647	-0.00670	0.16329	0.02198	0.33812	0.34383	1

Dry season correlation structure

The dry season correlation matrix (Table 4) displayed markedly weaker and more heterogeneous relationships among metals compared with the wet season, despite a similar sample size (n=40). Most correlation coefficients were in the weak to moderate range, and only a few pairs exceeded |r|=0.5, indicating that under dry conditions metals respond more to localized sources and site-specific processes than to a single dominant contamination mechanism.

The strongest structure in the dry season was centered on Zn and Cr: Zn–Cr showed a moderate correlation of r=0.5965, while Zn–Cd (r=0.4742), Zn–Ni (r=0.4973), Cr–Cd (r=0.3793) and Cr–Co (r=0.3438) suggested partial co-variation among Zn, Cr, Cd, Ni and Co (generally $p<0.05$). This pattern may reflect combined effects of atmospheric deposition, dust resuspension and local waste inputs that act more independently of runoff in the dry season, with Zn and Cr acting as indicators of mixed industrial influence. Copper and lead retained a significant association (Cu–Pb r=0.4626, $p<0.01$), consistent with their co-occurrence in battery terminals and electrical connections, but Pb correlations with other metals were weak (e.g., Pb–Zn r=0.2076, Pb–Cd r=0.0362), highlighting a more restricted linkage than in the wet period.

Many metal pairs involving Fe showed low or even slightly negative correlations (Fe–Ni r=−0.1093, Fe–Cr r=−0.1110), and several Co and Mn relationships were only modest (Mn–Zn r=0.3734, Co–Mn r=0.3541). Given the approximate sample size, these weaker coefficients fall at or below typical significance thresholds and likely indicate no robust linear association. This fragmentation of the correlation network in the dry season suggests that declining moisture and the absence of intense surface runoff reduce the hydrological coupling among metals, allowing each element's individual geochemical behavior, grain-size partitioning and localized deposition to play a larger role.

Implications and seasonal contrast

Taken together, the correlation results demonstrate a clear seasonal contrast in heavy-metal co-behavior at the study site: the wet season is characterized by strong, statistically significant multi-metal correlations indicative of a common anthropogenic source and efficient hydrological mixing, whereas the dry season shows weaker and more scattered relationships consistent with localized inputs and reduced co-transport. Similar seasonal shifts in correlation structure and source apportionment have been documented in industrial and waste-impacted soils, where increased rainfall enhances metal mobility and co-dispersion, while dry conditions promote spatial heterogeneity and dust-dominated pathways. These findings support the conclusion that rainfall and runoff are key drivers of multi-metal contamination dynamics around the battery recycling facility and justify the emphasis on wet-season measurements in ecological and human-health risk assessments.

Seasonal assessment of heavy metal pollution and ecological risk using multi-index evaluation

Tables 5 and 6 present contamination factor (CF), geoaccumulation index (IGEO), enrichment factor (EF) and ecological risk index (ERI) for heavy metals in soils from the study site, evaluated separately for the wet and dry seasons. These indices were used to quantify the degree of contamination, anthropogenic enrichment and potential ecological risk associated with the measured metal concentrations. Background concentrations (Cbg) were taken from Kabata-Pendias (2011), representing typical trace-element levels in uncontaminated soils (Cu 25.0, Zn 70.0, Pb 20.0, Mn 850.0, Fe 38 000.0, Co 8.0, Cd 0.3, Cr 90.0, Ni 50.0 mg/kg). CF compares observed concentrations with these background values, IGEO expresses pollution intensity on a logarithmic scale, EF (normalized to Fe) evaluates anthropogenic enrichment relative to crustal composition, and ERI combines contamination level with metal-specific toxic-response factors (Tr) to indicate potential ecological harm. Toxic-response factors followed widely used values (Cd 30.0; Pb and Cu 5.0; Zn 1.0; Cr 2.0; Ni 5.0; Co 2.0; Mn and Fe 1.0), which are appropriate for ecological risk screening.

Wet season: dominance of cadmium

In the wet season, (Table 5), CF values showed that Cd was extremely enriched relative to background (CF ≈ 55.6), whereas Cu, Pb and Co exhibited moderate contamination (CF ≈ 0.6–0.8) and the other metals had low contamination (CF < 0.2). IGEO values reinforced this pattern, with only Cd displaying IGEO > 5.0, corresponding to extremely polluted conditions, while all other metals had negative IGEO and were therefore classified as unpolluted with respect to backgrounds. values. EF values normalized to Fe indicated very strong anthropogenic contributions for Cd, with EF values several orders of magnitude above unity, and substantial enrichment for Cu, Pb and Co (EF > 20–40, a range typically associated with significant anthropogenic inputs), whereas Mn and Fe had EF ≈ 1.0, confirming their predominantly geogenic origin. When CF values were combined with the toxic-response factors, the ecological risk index ERI was overwhelmingly dominated by Cd (ERI ≈ 1669.0), placing Cd in the "very high ecological risk" category, while all other metals had ERI < 5, consistent with low ecological risk despite measurable contamination.

Overall, the wet-season indices clearly identify cadmium as the principal driver of ecological hazard at the site, with other metals playing only minor roles in risk despite evidence of anthropogenic enrichment. These results are consistent with previous reports that Cd, Pb and Cu are closely linked to industrial and urban sources, including battery recycling and related activities (Kabata-Pendias, 2011; Singh *et al.,* 2005).

Dry season: Reduced but still critical Cd risk

In the dry season, (Table 6), the same indices confirmed that Cd remained the key contaminant, although at lower levels than in the wet season. The Cd contamination factor decreased to about 20.8, which still represents very high contamination, while Co showed CF slightly above 1.0 (moderate contamination), Cu and Pb had CF around 0.4, and the remaining metals were below 0.2 (low contamination). IGEO again identified Cd as the only metal in the strongly polluted range (IGEO ≈ 4.5), whereas all other elements had IGEO < 0 and were therefore unpolluted relative to background. Dry-season EF values remained extremely high for Cd, confirming a persistent, strong anthropogenic signal, and were also large for Co, indicating significant enrichment of this metal in the absence of intense runoff. The other metals showed moderate EF values consistent with mixed natural and human influence. ERI for Cd, although reduced to about 624.0, still fell within the "very high risk" class according to Hakanson-type criteria, whereas ERI values for the other metals remained well below threshold levels for concern (all < 3.0). Thus, even in the dry season, ecological risk is overwhelmingly controlled by cadmium, with other metals contributing very little to the overall risk profile.

Seasonal contrast and implications

Comparison of the two seasons shows that all four indices consistently indicate greater impact in the wet season than in the dry season, particularly for Cd. Wet-season Cadmium CF and ERI values are roughly two to three times higher than their dry-season counterparts, indicating that rainfall and associated surface runoff substantially enhance cadmium mobility, accumulation and ecological threat in soils around the battery recycling site. For the other metals, seasonal differences in CF, IGEO and ERI are relatively small, and all remain below levels typically considered indicative of serious ecological pollution when evaluated against Kabata-Pendias, (2011) background values. These findings imply that, within this background-corrected framework, risk management and remediation efforts should prioritize cadmium, especially during and immediately after the wet season when both contamination intensity and ecological risk are greatest. The consistently low IGEO and ERI values for Fe and Mn reinforce their interpretation as largely geogenic reference elements, while elevated EF but low ERI for Cu, Pb and Co indicates anthropogenic enrichment that does not yet translate into high ecological risk at the measured concentrations. Taken together, the indices provide a coherent picture of site contamination: a multi-metal anthropogenic signature dominated ecotoxicologically by cadmium, modulated seasonally by hydrological conditions, and best interpreted using soil-appropriate background values and the ecological risk framework of Hakanson (1980) & Kabata-Pendias (2011).

Table 5: Heavy metal pollution and ecological risk using multi-index evaluation (wet season)

Metal (mg/kg)	**CF (wet)**	**IGEO (wet)**	**EF (wet)**	**Tr**	**ERI (wet)**
Cu	0.618000	−1.11	≈ 33.00	5.0	3.09000
Zn	0.187000	−3.00	≈ 11.00	1.0	0.19000
Pb	0.693000	−1.28	≈ 37.00	5.0	3.47000
Mn	0.014800	−6.66	≈ 0.82	1.0	0.01500
Fe	0.000475	−11.95	1 (ref.)	1.0	0.00048
Co	0.841000	−0.45	≈ 45.00	2.0	1.68000
Cd	55.620000	5.63	>>1000.00	30.0	1668.60000
Cr	0.051900	−4.84	≈ 3.00	2.0	0.10400
Ni	0.195000	−2.87	≈ 11.00	5.0	0.97300

Table 6: Heavy metal pollution and ecological risk using multi-index evaluation (dry season)

Metal (mg/kg)	CF	IGEO	EF	Tr	ERI
Cu	0.428	−1.53	≈ 32.0	5.0	2.14
Zn	0.125	−3.39	≈ 9.8	1.0	0.13
Pb	0.444	−1.76	≈ 33.0	5.0	2.22
Mn	0.0182	−6.36	≈ 1.1	1.0	0.018
Fe	0.000379	−12.27	1.0	1.0	0.00038

Co	1.26	−0.02	≈ 92.0	2.0	2.52
Cd	20.79	4.45	>> 10^3	30.0	623.7
Cr	0.0838	−4.16	≈ 4.8	2.0	0.168
Ni	0.111	−3.17	≈ 8.6	5.0	0.555

CONCLUSION

The assessment of heavy metals across wet and dry seasons reveals cadmium (Cd) as the most critical pollutant, with consistently high values in all contamination indices, especially during the wet season, where runoff and increased water flow likely enhance its mobility and ecological impact. The more substantial amounts of Pb, Cu, and Ni further suggest to prolonged human effect, possibly from industrial discharge and urban activity. In contrast, naturally occurring elements like Fe and Mn retained low contamination levels, indicating limited human intervention. Seasonal fluctuations noticeably altered metal behavior, with lower CF and ERI values in the dry season and lowered IGEO values across most metals, suggesting less dispersion owing to restricted hydrological movement. This seasonal dynamic validates prior results on the critical impact of rainfall and runoff in heavy metal transport and bioavailability. In general, our results point out the critical need for monitoring and managing Cd pollution, particularly during the rainy season, to limit its ecological effects.

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