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Carcinogenic and Non-Carcinogenic Health Risk Assessment of Heavy Metal Exposure at a Battery Recycling Site in Ogijo South West, Nigeria

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Abstract

Although recycling of batteries is economical and environmentally friendly, occupational and environmental heavy metal pollution is dangerous because of the health-threatening effects. This paper evaluated both carcinogenic and non-carcinogenic health risks caused by the exposure to heavy metal in a battery recycling plant in Nigeria in Ogun State, Ogijo. The analysis of nine heavy metals (Pb, Cd, Cr, Ni, Fe, Mn, Co, Zn, Cu) in water samples collected in wet and dry seasons was performed by the use of flame atomic absorption spectrophotometry. Chronic daily intake (CDI) was determined to ingestion and dermal exposure routes with risk being described by quotients of hazards (HQ) and hazard indices (HI) and incremental lifetime cancer risk (ILCR). Non-carcinogenic risk assessment gave an average hazard index of 0.014 (ingestion) and 0.00008 (dermal), which are less than the USEPA limit of 1.0, and this implies acceptable non-cancer risk levels. But the assessment

of carcinogenic risks showed collective ILCR of 3.12×10^{-4}, which is above the acceptable limit (1×10^{-6} to 1×10^{-4}). Lead and chromium were the greatest contributors to cancer risk (Pb: 1.54×10^{-4} wet season; Cr: 4.3×10^{-4} wet season). Dermal exposure was less risky as compared to ingestion pathways. Seasonal variation was found to have high levels of contaminants in wet season, which was due to industrial runoff. This paper explains why site remediation should be increased, occupational health standards should become more stringent, and regulation should be enforced to curb the exposure of heavy metals to the workers and neighbors.

Keywords: Battery recycling, Heavy metals, Health risk assessment, Carcinogenic risk, Incremental lifetime cancer risk, Environmental contamination, Nigeria.

Introduction

Batteries have become an essential part of contemporary electronics and energy storage devices that fuel the technological growth in the world. Nonetheless, the fast consumption and improper end of life disposition have brought about significant e-waste problems, and especially in third world countries (Botelho Junior *et al.,* 2021). Although battery recycling has such positive effects as environmental and economic advantages such as recovery of valuable metals and a decrease in the landfill burden, informal and poorly controlled recycling processes present a considerable occupational and environmental health problem (Binnemans *et al.,* 2013). Common in most developing nations, informal battery pyrolysis puts the workers and the local residents at risk of heavy metals via direct contact, inhalation, and ingestion routes (Rahman *et al.,* 2019). Primary health concerns are lead, cadmium, chromium, and nickel because they are carcinogenic and systemic toxicants (Hossain *et al.,* 2018). Research shows that it is economically feasible to recycle nickel and cobalt batteries to recover them instead of primary mining and produce fewer carbon emissions. However, when recycling activities are not associated with adequate environmental precautions and occupational health precautions, they become a major source of pollution.

Heavy Metals and Health Effects

The toxicity, low biodegradability and potential bioaccumulation of heavy metals in water and soil are peculiarities of their hazards (Saxena *et al.,* 2019). Such toxins inhibit the metabolic processes, prevent the activity of the enzymatic activity, and accumulate in target organs such as the brain, liver, kidneys, and bones (Mohammadi *et al.,* 2019). Some metals (iron, zinc, copper) are important physiologically at low doses, but chronic exposure is above the safe dose, and causes severe health effects (Thompson *et al.,* 2021).

Lead causes damage to the nervous system, kidney disorders and reproductive damage (Needleman, 2004). Cadmium is a human carcinogen, which is deposited in the kidney leading to renal dysfunction (IARC, 2012).

Chromium occurs in essential (trivalent) and carcinogenic (hexavalent) forms whose latter induces lung cancer plus gastrointestinal (GI) disruptions (Wise and Wise, 2012). Nickel is a respiratory sensitizer and a potential human carcinogen (Gawkrodger, 2003).

Health Risk Assessment Framework

Human health risk assessment involves the methodical analysis of exposure to the contaminants and the related health effects (USEEPA, 1989). The USEPA model includes four parts: identification of hazard, exposure assessment, dose response assessment, and risk characterization. The methodology entails the quantitative approximations of the risk of both cancer and non-cancer by combining the concentrations of contaminants, exposure pathways, toxicity information, and population-specific parameters (Wang *et al.,* 2005). In the case of water-borne heavy metals, ingestion and dermal intake are the main exposure routes (Wu *et al.,* 2020). The total daily intake (CDI) of each pathway is computed and defined in terms of reference doses (non-carcinogenic risk) or cancer slope factors (carcinogenic risk) (Zheng *et al.,* 2010). The non-carcinogenic risk is in terms of hazard quotients (HQ) and hazard indices (HI) with values lower than one showing acceptable risk (USEPA, 2004). The measure of carcinogenic risk is incremental lifetime cancer risk (ILCR), and acceptable thresholds are 1×10^{-6} to 1×10^{-4} (Prasad *et al.,* 2020, Rahman *et al.,* 2019).

Problem Statement

The informal battery recycling industry in Nigeria has no proper regulatory measures, environmental measures, and health workplace safety. In Ogun State, there is a large number of unregulated recycling activities in Ogijo, which cause heavy metal pollution. Past research records high levels of soil and water contamination in this location (Adeleke *et al.,* 2023); nevertheless, there is limited evidence on quantifying the health risk of combined carcinogenic and non-carcinogenic impacts of the seasonal variations in the area. This is the knowledge gap that this study will answer because it will perform integrated risk assessment on various heavy metals and pathways of exposure in contrast between the climatic seasons to give evidence-based recommendations that can lead to site remediation and policy intervention. This study aims to evaluate the carcinogenic and non-carcinogenic risks of heavy metals in water samples from Ogijo, Ogun State, across seasonal variations.

Materials and Methods

Study Area Description

The research area is at Ogijo, South-west, Nigeria (latitude: 6º 43᾽ 35.00᾽᾽ N to 6º 42᾽ 40.00᾽᾽ N; longitude: 3º 31᾽.00º E to 3º 31᾽ 60.00᾽᾽ E). The location is in Shagamu Local Government Area, which lies between Lagos and Ibadan, south-western Nigeria. The terrain bears the features of tropical climate that has wet and dry seasons. The Yoruba Remo branch was founded in the mid-1800s as Shagamu that now serves as an important industrial and commercial center and incorporates many manufacturing and recycling enterprises (Adeleke *et al.,* 2023). Geological

substrate is mainly made up of laterites and alluvial that are characteristic of the area, and which affect the mobility and bioavailability of contaminants.

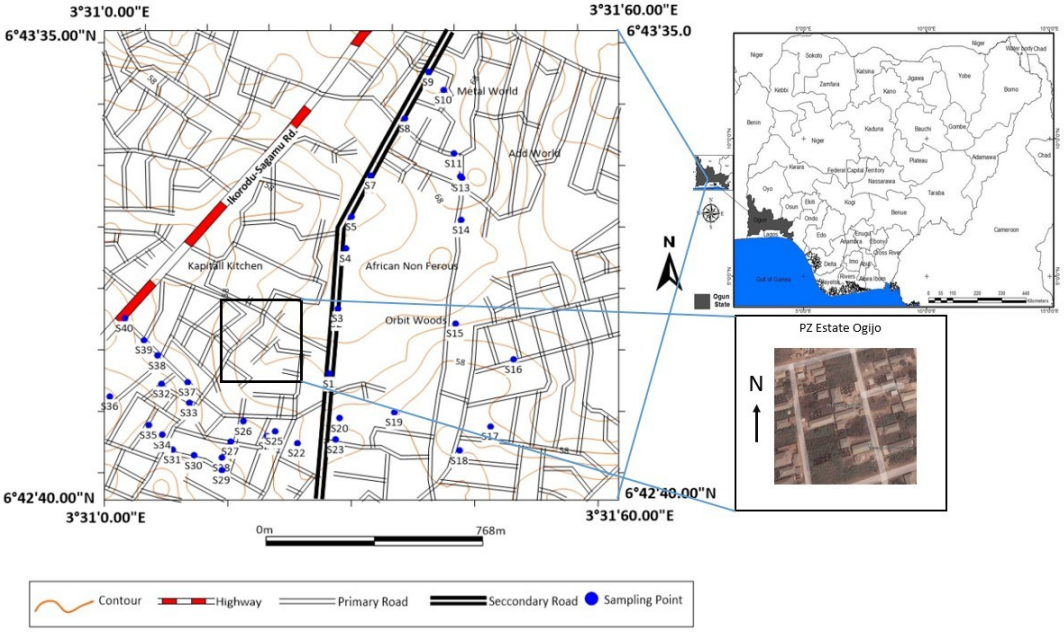


Figure 1: The points of sample collection are indicated in the geographic map.

The water samples (n= 80) were sampled at various points randomly (between 5 and 10 meters) and during wet and dry seasons (n= 40 each season) in the active battery recycling facility. The sampling sites were allocated to be able to sample spatial variability of the contamination patterns. All the collection vessels were washed with deionized water and ethanol to pre-sample the vessel to remove the risk of cross-contamination. At the time of analysis, samples were contained in acid-washed polyethylene bottles that were stored at 4°C before analysis, which was done within 48 hours of sampling.

Digestion of water samples (50 mL) was performed with concentrated nitric acid (HNO_3, 5 mL/sample) according to the EPA Method 3010A. The samples were heated in a hot plate until 5 mL was left and cooled and diluted to 25 mL using deionized water (Ohimain *et al.,* 2012). Quality control Procedural blanks (distilled water, which had undergone the same digestion) were determined. The determination of heavy metal was done using the Buck Scientific Model PG 990 Flame Atomic Absorption Spectrophotometer (FAAS) using the certified reference standards. Nine metals (Lead (Pb), Cadmium (Cd), Chromium (Cr), Nickel (Ni), Iron (Fe), Manganese (Mn), Cobalt (Co), Zinc (Zn) and Copper (Cu) were analyzed. The instrument drift was also observed through the repeated analysis of quality control standards (coefficient of variation <5%).

The heavy metals were then analyzed and the mean, standard deviation, variance, standard error and 95% confidence intervals of each of the metals and seasons (n=40) were analyzed. All the statistics of the active and inactive seasons were gathered in the (Supplementary Tables

M and N) and the seasonal tendencies were graphically represented by the bar charts of error bars of 95 percent in the Supplementary Figures M and N. A grouped bar chart in which blue (wet) and red (dry) bars have been plotted and 95% intervals are drawn against each other (Supplementary Figures (O) has been performed to demonstrate the change in the level of metals in the soil between seasons. Overview Supplementary Material. In Supplementary Tables M and N, detailed seasonal summary statistics were given in all nine metals. Such tables give means, standard deviations, standard errors, and 95 percent confidence intervals of dry and wet seasons (n = 40 each). Direct mean comparison is provided in Supplementary Table O. Bar charts with 95 percent confidence intervals illustrating apparent seasonal differences in a number of metals are given in Supplementary Figures M, N, and O and can be used to describe the manner in which the measured concentrations vary. These ranges of statistics define the seasonal fluctuation that subsequently shapes the values of CDI, HQ, HI, and ILCR.

Methodology of Risk Assessment

Computation of Chronic Daily Intake. Ingestion and dermal CDI (Mg/kg/day) were calculated using Equations of the USEPA standard Ingestion pathway:

where Cw = concentration of metal in water (mg/L); DI = daily water consumption (2 L/day); ABS = fraction of gastrointestinal absorption (0.01); EF = frequency of exposure (365 days/year); ED = length of exposure (30 years); BW = body weight (70 kg adult); AT averaging time of exposure 365 x ED in non-carcinogenic biomagnifiers; 365 x 70 in carcinogenic biomagnifiers (25,550 days)

Dermal pathway: where: SA = surface area of the skin (18,000 cm^2 = 1.8 m^2); Kp = dermal permeability coefficient (cm/hr) and ET = time of exposing the skin to water (1 hour/day); CF = unit conversion factor (0.001 L/cm^3); other parameters as defined above. The Non-Carcinogenic Risk Characterization is as follows.

Metal and pathway

Hazard Quotient (HQ): where: RfD = reference dose (mg/kg-day) based on USEPA toxicity databases and on scientific literature. Hazard Index (HI) that is the cumulative non-carcinogenic risk of various metals: HI < 1.0 represents the acceptable risk of non-cancer; HI > 1.0 denotes the possible negative health outcomes (Huang *et al.,* 2008).

Characterization of risk in the form of carcinogen

Increments of Lifetime Cancer risk (ILCR) of carcinogenic metals: where: CSF = cancer slope factor (mg/kg/day), which is the carcinogenic strength per unit of exposure. The risk assessment of carcinogens involved Pb, Cd, Cr and Ni which are primary carcinogens. Combined ILCR was the likelihood of getting any type of cancer within 70 years of lifetime in response to 24 hours per day exposure (Prasad *et al.,* 2020). Acceptable ILCR threshold: 1×10^{-6} (1 in a million) to 1×10^{-4} (1 in 10,000).

All the values of toxicity (RfD, CSF) were obtained through the USEPA Integrated Risk Information System (IRIS), literature and the guidelines of the international health organizations. The exposure parameters were standardized based on the common occupational and residential situations in the tropical developing-country situations.

Table 1: Equations, variables, units, and exposure parameters used for non-carcinogenic and carcinogenic health risk assessment.

Category	Parameter / Equation	Description	Unit	Value	Reference
Exposure Assessment	$CDI_{\{ing\}} = (Cw \times DI \times ABS \times EF \times ED) / (BW \times AT)$	Chronic daily intake via ingestion	mg kg^{-1} day^{-1}		USEPA (1989)
	$CDI_{derm} = (Cw \times SA \times Kp \times ET \times EF \times ED \times CF) / (BW \times AT)$	Chronic daily intake via dermal contact	mg kg^{-1} day^{-1}		USEPA (2004)
Concentration	Cw	Metal concentration in water	mg L^{-1}	Measured	This study
Ingestion Parameters	DI	Daily water ingestion rate	L day^{-1}	2.0	USEPA
	ABS	Gastrointestinal absorption factor	—	0.01	Literature
Dermal Parameters	SA	Exposed skin surface area	cm^2	18,000	USEPA
	Kp	Dermal permeability coefficient	cm h^{-1}	Metal-specific	USEPA
	ET	Exposure time	h day^{-1}	1.0	USEPA
	CF	Unit conversion factor	L cm^{-3}	0.001	USEPA
Exposure Duration	EF	Exposure frequency	days $year^{-1}$	365	USEPA
	ED	Exposure duration	years	30	USEPA
	BW	Body weight (adult)	kg	70	USEPA
	AT (non-cancer)	Averaging time	days	365 × ED	USEPA
	AT (cancer)	Averaging time	days	365 × 70	USEPA
Non-Carcinogenic Risk	HQ = CDI / RfD	Hazard quotient			USEPA
	RfD	Reference dose	mg kg^{-1} day^{-1}	Metal-specific	IRIS
	HI = ΣHQ	Hazard index			USEPA
Carcinogenic Risk	ILCR = CDI × CSF	Incremental lifetime cancer risk			USEPA
	CSF	Cancer slope factor	(mg kg^{-1} $day^{-1})^{-1}$	Metal-specific	IRIS
Risk Criteria	HI < 1	Acceptable non-carcinogenic risk			USEPA
	ILCR	Acceptable cancer risk range		10^{-6}–10^{-4}	USEPA

Results and Discussion

The Non-Carcinogenic Health Risk Assessment

The hazard quotient methodology was used to assess both the ingestion and dermal routes of nine heavy metals as non-carcinogenic risks (Tables 2 and 3).

The Connection between Metal Variability and Risk Calculations

Since CDI, HQ, HI and ILCR are proportional to the levels of contaminants, the variation reflected in the Supplementary Tables M and N is directly related to the uncertainty in risk values presented in this section. According to the seasonal bar graphs (Supplementary Figures M and N), the means of dry and wet seasons tend to be different and that many metals have the 95 percent confidence intervals with minimal overlapping. These trends can be used to explain why the wet season risk values are higher and why chromium, lead and cadmium occupy the majority of the non-carcinogenic and the carcinogenic pathways.

Table 2: Non-Carcinogenic Risk Assessment Ingestion Pathway.

Heavy Metal	Wet Season			Dry Season		
	CDI (mg/kg-day)	RfD (mg/kg-day)	HQ	CDI (mg/kg-day)	RfD (mg/kg-day)	HQ
Pb	1.81×10^{-5}	3.60×10^{-3}	0.005029	1.51×10^{-5}	3.60×10^{-3}	0.004198
Cd	1.46×10^{-5}	3.00×10^{-3}	0.004858	1.15×10^{-5}	3.00×10^{-3}	0.003831
Cr	1.05×10^{-5}	3.00×10^{-3}	0.003494	8.94×10^{-6}	3.00×10^{-3}	0.002980
Ni	8.32×10^{-6}	2.00×10^{-2}	0.000416	1.92×10^{-6}	2.00×10^{-2}	0.000096
Fe	1.71×10^{-5}	7.00×10^{-2}	0.000244	1.89×10^{-5}	7.00×10^{-2}	0.000270
Mn	1.32×10^{-5}	Not Assigned	N/A	1.28×10^{-5}	Not Assigned	N/A
Co	1.20×10^{-5}	2.00×10^{-2}	0.000600	9.42×10^{-6}	2.00×10^{-2}	0.000471
Zn	7.08×10^{-6}	3.00×10^{-1}	0.000024	5.63×10^{-6}	3.00×10^{-1}	0.000019
Cu	1.16×10^{-5}	3.70×10^{-2}	0.000314	1.12×10^{-5}	3.70×10^{-2}	0.000302
HI (Ingestion)			**0.014978**			**0.012656**
Average HI	(0.014978 + 0.012656) / 2 = **0.0138**					

Heavy metal concentrations (CDI), reference doses (RfD), and hazard quotients (HQ) for wet and dry seasons. Values represent chronic daily intake normalized to reference toxicity thresholds. HI is the cumulative hazard index across all metals.

Table 3: Non-Carcinogenic Risk Assessment Dermal Pathway.

Heavy Metal	Wet Season			Dry Season		
	CDI dermal (mg/kg-day)	RfD (mg/kg-day)	HQ	CDI dermal (mg/kg-day)	RfD (mg/kg-day)	HQ
Pb	3.53×10^{-8}	3.60×10^{-3}	9.81×10^{-6}	2.95×10^{-8}	3.60×10^{-3}	8.19×10^{-6}
Cd	1.71×10^{-7}	3.00×10^{-3}	5.68×10^{-5}	1.34×10^{-7}	3.00×10^{-3}	4.48×10^{-5}
Cr	4.09×10^{-8}	3.00×10^{-3}	1.36×10^{-5}	3.49×10^{-8}	3.00×10^{-3}	1.16×10^{-5}
Ni	3.24×10^{-9}	2.00×10^{-2}	1.62×10^{-7}	7.48×10^{-10}	2.00×10^{-2}	3.74×10^{-8}
Fe	3.67×10^{-7}	7.00×10^{-2}	5.24×10^{-6}	4.05×10^{-7}	7.00×10^{-2}	5.79×10^{-6}
Mn	2.57×10^{-8}	Not Assigned	N/A	2.50×10^{-8}	Not Assigned	N/A
Co	2.34×10^{-8}	2.00×10^{-2}	1.17×10^{-6}	1.84×10^{-8}	2.00×10^{-2}	9.19×10^{-7}
Zn	8.28×10^{-8}	3.00×10^{-1}	2.76×10^{-7}	6.59×10^{-8}	3.00×10^{-1}	2.20×10^{-7}
Cu	2.26×10^{-8}	3.70×10^{-2}	6.11×10^{-7}	2.18×10^{-8}	3.70×10^{-2}	5.89×10^{-7}
HI(Dermal)			**0.000087**			**0.000072**
Average HI	(0.000087 + 0.000072) / 2 = **0.000080**					

Heavy metal concentrations via dermal uptake (CDI dermal), reference doses, and hazard quotients for wet and dry seasons. HI = cumulative hazard index; dermal exposures substantially lower than ingestion due to reduced bioavailability of the dermal contact.

The hazard indices in both ingestion and dermal routes were far below the USEPA standard of 1.0. HI (HI 0.0138 average) in ingestion table 2, was about 170-fold greater than dermal HI (HI 0.000080 average) table 3, which is equal to differences in bioavailability between transdermal and gastrointestinal preferential uptake. The highest contribution in terms of ingestion risk came with lead, cadmium and chromium (cumulative HQ = 0.0126) and other metals contributed insignificantly. There was a small, slightly higher HI (0.0150) in wet season than in dry season (0.0127), which can be explained by further mobilization of aqueous contaminants during industrial runoff and precipitation.

Both routes show non-carcinogenic risk levels at acceptable levels, and this implies that the likelihood of acute or chronic systemic toxicity or organ dysfunction due to acute or chronic heavy metal exposure through this water source at the current concentration levels is low. Nevertheless, such a conclusion is valid to the study area only and not applicable to other exposure routes (inhalation, soil ingestion, dietary intake) and other vulnerable populations (children, pregnant women, occupationally exposed workers).

Health Risk Assessment on the Carcinogenicity of the Substance

Four known carcinogenic metals were assessed as the risk of cancer; Lead (Pb), Cadmium (Cd), Chromium (Cr) and Nickel (Ni). CSF were used to apply cancer slope factors (CSF) to the CDI estimates of both pathways.

Table 4: Risk Assessment Ingestion Pathway of Carcinogens.

Heavy Metal	Wet Season			Dry Season		
	CDI Ingestion (mg/kg-day)	CSF (mg/kg-day)	ILCR	CDI Ingestion (mg/kg-day)	CSF (mg/kg-day)	ILCR
Ni	8.32×10^{-6}	0.84	6.99×10^{-6}	1.92×10^{-6}	0.84	1.61×10^{-6}
Cd	1.46×10^{-5}	6.10	8.91×10^{-5}	1.15×10^{-5}	6.10	7.01×10^{-5}
Pb	1.81×10^{-5}	8.50	1.54×10^{-4}	1.51×10^{-5}	8.50	1.28×10^{-4}
Cr	1.05×10^{-5}	41.0	4.31×10^{-4}	8.94×10^{-6}	41.0	3.67×10^{-4}
Total ILCR (Ingestion)			$\mathbf{6.78 \times 10^{-4}}$			$\mathbf{5.67 \times 10^{-4}}$
Average ILCR (Ingestion)	$(6.78 \times 10^{-4} + 5.67 \times 10^{-4}) / 2 = \mathbf{6.23 \times 10^{-4}}$					

Chronic daily intakes (CDI), cancer slope factors (CSF) and incremental lifetime cancer risk (ILCR) of four carcinogenic heavy metals in wet and dry seasons. ILCR values are the likelihood of contracting any type of cancer over lifetime (70 years) at the continuum of daily exposure.

Table 5: Carcinogenic Risk Assessment Dermal Pathway.

Heavy Metal	Wet Season			Dry Season		
	CDI Dermal (mg/kg-day)	CSF (mg/kg-day)	ILCR	CDI Dermal (mg/kg-day)	CSF (mg/kg-day)	ILCR
Ni	3.24×10^{-9}	0.84	2.72×10^{-9}	7.48×10^{-10}	0.84	6.28×10^{-10}
Cd	1.71×10^{-7}	6.10	1.04×10^{-6}	1.34×10^{-7}	6.10	8.17×10^{-7}
Pb	3.53×10^{-8}	8.50	3.00×10^{-7}	2.95×10^{-8}	8.50	2.51×10^{-7}
Cr	4.09×10^{-8}	41.0	1.68×10^{-6}	3.49×10^{-8}	41.0	1.43×10^{-6}
Total ILCR (Dermal)			**3.02×10^{-6}**			**2.43×10^{-6}**
Average ILCR (Dermal)	$(3.02 \times 10^{-6} + 2.43 \times 10^{-6}) / 2 =$ **2.73×10^{-6}**					

In table 4, The carcinogenic risk was dominated by chromium through ingestion pathway (average ILCR = 4.31×10^{-4} wet season; 3.67×10^{-4} dry season), then lead (1.54×10^{-4} wet; 1.28×10^{-4} dry) and then cadmium (8.91×10^{-5} wet; 7.01×10^{-5} dry). Nickel made a small (less than 2×10^{-6}) contribution. Transdermal bioavailability was very low, as dermal pathway ILCR values were non-significant (average = 2.73×10^{-6}).

Combined Risk Assessment: Combined ILCR (ingestion and dermal averaged seasonally): This total ILCR 3.12×10^{-4} (a little over 1 in 3,200 excess cases of cancer per exposed population) is above the USEPA range of acceptability (1×10^{-6} to 1×10^{-4}), and would mean that continuous exposure at the present levels of contamination might not likely be carcinogenic.

Seasonal Pattern Analysis

The wet season had a greater ILCR than dry season in both pathways and this was in agreement with the higher aqueous metal mobilization in precipitation and the related industrial run off. The difference in ingestion ILCR between wet and dry season was almost twice (an average difference of 20% between wet and dry) (6.78×10^{-4} and 5.67×10^{-4}, respectively), indicating that seasonal remediation and industrial discharge management would offer quantifiable health gains.

Characterization of Risk and Comparative Evaluation

Pathway Dominance

Ingestion was by far the most significant source of total carcinogenic risk with a contribution of over 99.5% of total ILCR. This indicates the much higher bio-availability of ingested compared to dermally absorbed heavy metals, which is in line with mechanistic knowledge of gastrointestinal absorption (absorption fraction of most metals is 1-2%), in comparison with transdermal uptake (penetration coefficient is equal to orders of magnitude less).

Profiles of Metal Specific Risk

Chromium: This is the highest contribution to cancer risk in terms of the highest CSF (41 mg/kg-day)$^{-1}$, which is the carcinogenic pentavalent chromium (Wise and Wise, 2012). Oxidative stress (Cr (VI) causes chromosomal aberrations and DNA damage (Ye *et al.,* 1999). Doses of the study (Cr is 1.05×10^{-5} to 8.94×10^{6} mg/kg/day ingestion CDI) produce large personal risks of cancer.

Lead is the second biggest risk factor, despite lower CSF (8.5 mg/kg/day) because it has greater concentrations in water. Lead's mechanism includes oxidative stress, epigenetic alterations, and compromised DNA repair (Needleman & Bellinger, 2000). Studies on occupational exposure show that cancer is linked to the amount of exposure (Steenland & Boffetta, 2012).

Cadmium: The third contributor, with a CSF of 6.1 mg/kg/day), shows that it can cause cancer in the kidneys and testicles in animal models (IARC, 2012). Cadmium's extended biological half-life (about 30 years in the kidneys) indicates an accumulative danger associated with chronic exposure (Tellez-Plaza *et al.,* 2013).

Nickel: Minimal ILCR contribution despite Ni carcinogenicity, due to relatively low aqueous concentrations and substantial CSF (0.84 mg/kg-day)$^{-1}$.

The 95 percent interval of metal levels measured indicates a similar interval of risk values, especially for Pb, Cd, Cr, and Ni, because CDI, HI, and ILCR are directly proportional to the amount of contaminants in the exposure equations. If the concentrations in the dry season are higher and more variable, the dry season CDI, HI, and ILCR values would be greater and less certain. The risk levels shown in the main body of the article should be understood in light of the variability and confidence intervals shown in the supplementary material.

Comparison with Epidemiological Evidence

The predominance of chromium and lead as carcinogenic risks corresponds with industrial hygiene and epidemiological studies indicating increased cancer rates among workers involved in chromium plating, welding, and lead processing. This consistency confirms the exposure model's applicability to occupational environments and informal recycling activities.

Limitations and Uncertainties

Calculated risk estimations have built-in uncertainties that must be recognized:

i. Reference value uncertainty: RfD and CSF levels have geometric standard deviations that usually range from 3 to 10 times, which is due to extrapolation from animal research and differences across people (Slob *et al.,* 1999).
ii. Variability in exposure parameters: Standard assumptions (2 L/day water consumption, 70 kg body weight, 70-year exposure length) may overestimate or underestimate real occupational exposures.

iii. Temporal variability: Sampling during only one wet and dry season does not completely reflect how pollutant levels change from year to year or even from day to day.
iv. Missing exposure routes: This evaluation does not include breathing in dust and vapour, eating soil, or eating metals that have built up in the body, all of which might be important at recycling sites.
v. Diversity in the population: Risk estimations rely on average adult parameters, which may lead to an underestimation of the susceptibility of children, pregnant women, and those with impaired renal or hepatic function. Even with these restrictions, an ILCR that is higher than tolerable level is strong proof of a cancer risk that has to be dealt with.

Recommendations

Based on these results, we suggest that government organizations, businesses, and public health officials take the following steps:

Interventions at the site level

Remediation and Containment:

i. Use designed containment systems like impermeable liners and collecting sumps to keep contaminants from getting into groundwater (USEPA, 2008).
ii. Clean up the soil by focusing on the top layers (0–30 cm) that are most likely to be exposed to workers.
iii. Set up buffer zones (at least 100 meters) between recycling facilities and homes (WHO, 2011).

Seasonal Operational Controls:

i. Improve the control of wet-season discharge by using effluent treatment technologies (precipitation, flocculation, ion exchange) to lower the concentration of metals in water by at least 50%.
ii. Follow stormwater management rules that keep runoff from coming into touch with exposed ore and waste items as much as possible.

Occupational Health Measures:

i. Workers in the crushing, grinding, and melting zones must wear respiratory protection (P100/powered air-purifying respirators).
ii. Require workers who handle pre-sorted battery parts to wear gloves and other protective equipment to protect their skin.
iii. Make medical surveillance required, with yearly tests for blood lead levels and kidney function.

Suggestions for Rules and Policies

Limits on the amount of contaminants:

i. Set maximum contaminant limits (MCL) for recycling plant effluent that are legally binding: Pb 0.015 mg/L, Cd 0.005 mg/L, Cr 0.1 mg/L, Ni 0.1 mg/L. These values are in accordance with WHO guidelines and are harsher than Nigeria's present regulations.
ii. Set up frequent compliance checks (every three months) and punish people who don't follow the rules.

Formal Recycling Infrastructure:

i. Stop using uncontrolled, informal recycling operations and switch to certified facilities that include environmental regulations and protections for workers' health (UNEP, 2015).
ii. Give operators technical help and money to use the best available technology (BAT).

Land-Use Zoning:

i. Set aside areas for recycling activities that are not in populated areas and have to have buffer zones between them and water supplies and homes.
ii. Before giving licenses to new facilities, do environmental impact evaluations.

Suggestions for Community and Public Health

Reducing exposure:

i. Tell people who live near 500 meters to avoid drinking or using locally-harvested water for irrigation without extensive treatment (reverse osmosis, chelation) (ATSDR, 2007).
ii. Suggest adding calcium and iron to the diet of those who are at risk to lower the amount of heavy metals that their GI tract absorbs (Gena & Reilly, 2012).

Health Monitoring Program:

i. Set up baseline biomonitoring (blood Pb, urine Cd, plasma Cr) for workers and those who live nearby.
ii. Do health checks every three years, including checking for cancer and kidney function.

Public Awareness:

i. Teach people in the community about the health risks of heavy metal exposure and how to prevent it.
ii. Set up ways for workers to report health problems at work without fear of reprisal.

Conclusion

This comprehensive health risk evaluation uncovers divergent non-carcinogenic and carcinogenic profiles at the Ogijo battery recycling facility. The non-carcinogenic risk is still below tolerable levels for both ingestion and derma contact (HI = 0.0138 and 0.000080, respectively). This means that exposure to heavy metals in water alone is not very hazardous to the body. Nonetheless, carcinogenic risk assessment reveals significant apprehension, as the total ILCR of 3.12×10^{-4} (approximately 1 excess cancer case per 3,200 exposed persons

over a lifetime) beyond USEPA permissible thresholds (1×10^{-6} to 1×10^{-4}). Chromium and lead are the most important causes of cancer, and eating them is the main method people are exposed to them.

Seasonal fluctuation indicates heightened risk during the rainy season (+20% ILCR), signifying enhanced mobilization of aqueous contaminants due to industrial activities and precipitation-induced runoff. Because spatial risk is different in different places, we need to carefully describe the differences between occupational and residential exposure situations.

This study quantifies risk through water ingestion and dermal contact; however, a thorough risk assessment necessitates the incorporation of additional exposure pathways, particularly occupational inhalation exposure among recycling workers, soil ingestion, and dietary bioaccumulation, which likely significantly increase the overall health burden. These results show that the existing state of the Ogijo battery recycling facility poses an unacceptable cancer risk to health, which has to be addressed now. The right solutions are:

i. Better site cleanup and seasonal operating controls; and
ii. Setting enforceable regulatory limitations on the levels of contaminants in effluent.
iii. Ending informal recycling in favor of certified facilities with environmental controls.
iv. Land-use planning that keeps activities away from inhabited areas; and
v. Extensive health surveillance programs for workers and the community.

To protect Nigeria's expanding battery recycling industry as an economic and environmental resource, strong regulatory action is needed, together with technical and financial assistance. This would help reduce exposure to heavy metals. If we don't do anything, the health problems caused by work and the environment will continue to harm vulnerable people in developing nation industrial zones more than anybody else.

Role of Supplementary Statistical Ranges

The confidence intervals in Supplementary Tables M and N provide context for these uncertainties because they show the natural spread in measured metal concentrations. CDI, HI, and ILCR values in the main text with these ranges already interpreted.

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Appendix

Supplimentary Figures and Tables

Table M: Variability and 95% CI

Soil samples statistics table for wet season (ppm) for n = 40 per metal:

Metal (ppm)	n	Mean (ppm)	Variance (ppm²)	SD (ppm)	95% CI (ppm)
Mn	40.0	0.420	0.361	0.600	0.228–0.611
Cu	40.0	0.369	0.258	0.508	0.207–0.531
Zn	40.0	0.225	0.120	0.346	0.115–0.336
Ni	40.0	0.265	0.231	0.481	0.111–0.418
Cd	40.0	0.464	0.166	0.407	0.334–0.594
Fe	40.0	0.544	0.402	0.634	0.342–0.747
Pb	40.0	0.576	0.287	0.535	0.405–0.747
Cr	40.0	0.334	0.152	0.390	0.209–0.458
Co	40.0	0.382	0.216	0.465	0.233–0.530

a. Mean, variance, SD and CI are calculated from 40 raw soil measurements per metal.

b. This table directly provides the variance and 95% confidence intervals.
c. Mean soil concentrations of Pb and Cd were 0.576 ppm (95% CI: 0.405–0.747 ppm) and 0.464 ppm (95% CI: 0.334–0.594 ppm), respectively, indicating substantial variability across sampling points.

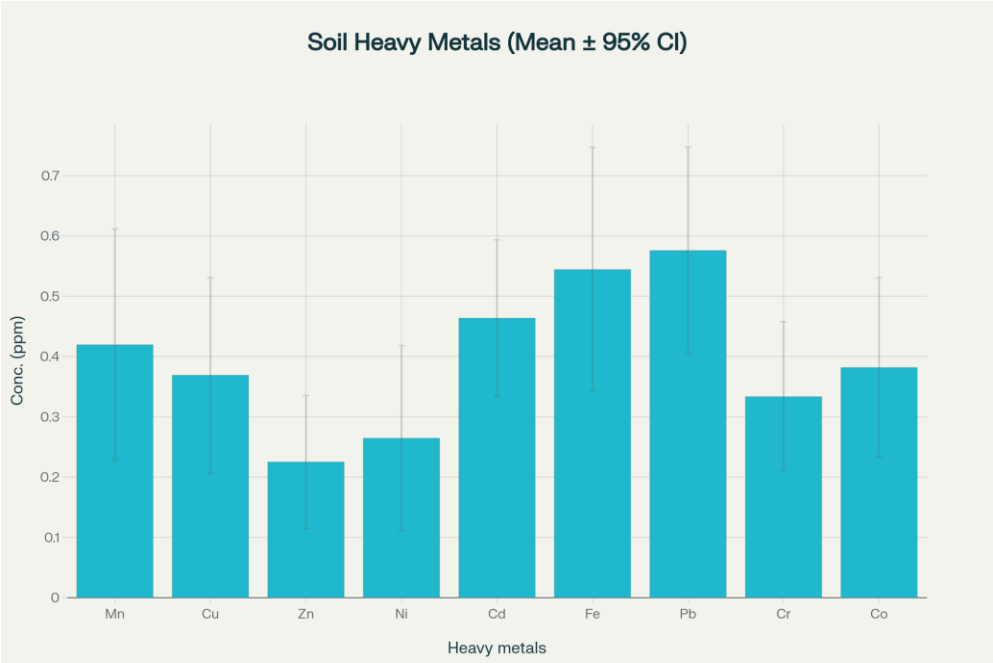


Figure M: Mean soil heavy metal concentrations (ppm) with 95% confidence intervals (n = 40 for each metal in Wet season)

Mean soil heavy metal concentrations (ppm) with 95% confidence intervals.

a. X-axis: Heavy metals (Mn, Cu, Zn, Ni, Cd, Fe, Pb, Cr, Co).
b. Y-axis: Concentration (ppm).
c. Bars: Mean concentration for each metal.
d. Error bars: 95% confidence interval (from CI low to CI high for each bar).
e. Variance: explicitly reported in the table for each metal.
f. Confidence intervals: 95% CI shown numerically in the table and visually as error bars in the figure.
g. Ranges / error bars: the CI bounds form a natural range; the error bars graphically highlight variability in your environmental measurements.

Table N: Dry season soil statistics table

Using 40 dry-season soil measurements per metal (ppm), the following statistics were calculated:

Metal (ppm)	n	Mean (ppm)	Variance (ppm²)	SD (ppm)	95% CI (ppm)
Fe	40.0	14.38	658.61	25.66	6.18–22.57
Mn	40.0	15.50	577.49	24.03	7.82–23.17
Cu	40.0	10.70	319.15	17.86	5.00–16.41
Zn	40.0	8.74	298.36	17.27	3.23–14.26
Ni	40.0	5.56	128.54	11.34	1.93–9.18
Cd	40.0	6.24	158.12	12.57	2.22–10.25
Pb	40.0	8.89	307.63	17.54	3.29–14.49
Cr	40.0	7.54	360.07	18.98	1.48–13.60
Co	40.0	10.06	315.71	17.77	4.38–15.73

a. Mean, variance, SD, and 95% CI are derived directly from dry-season soil raw data for each metal.
b. This table for the dry season parallels the wet-season table, satisfying the requirement for variance and confidence intervals across seasons.
c. During the dry season, mean soil Pb and Cd concentrations were 8.89 ppm (95% CI: 3.29–14.49 ppm) and 6.24 ppm (95% CI: 2.22–10.25 ppm), respectively, showing wide spatial variability.

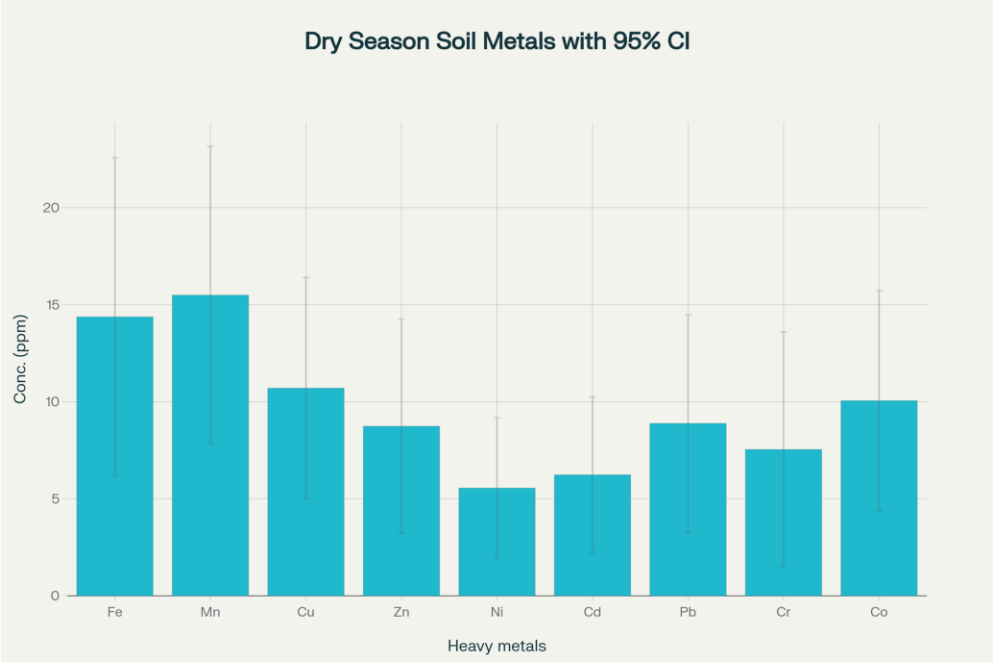


Fig N: Dry season mean soil heavy metal concentrations (ppm) with 95% confidence intervals.

a. X-axis: Heavy metals (Fe, Mn, Cu, Zn, Ni, Cd, Pb, Cr, Co).
b. Y-axis: Concentration (ppm).
c. Bars: Mean concentration for each metal.
d. Error bars: 95% confidence interval (from CI low to CI high for each metal).[2] "Figure Y. Dry season mean soil heavy metal concentrations (ppm) with 95% confidence intervals (n = 40 per metal).

Combining wet and dry season (means) in a single figure (grouped bars) to show seasonal differences with error bars.

USING COLOUR BLUE AND RED TO DIFFERENTIATE THE GRAPHICAL REPRESENTATION AND CONCISE EXPLANATION ON THE OVERALL RESULTS

a. X-axis: Mn, Cu, Zn, Ni, Cd, Fe, Pb, Cr, Co
b. Y-axis: Concentration (ppm)
c. Blue bars: wet-season mean with 95% CI error bars
d. Red bars: dry-season mean with 95% CI error bars

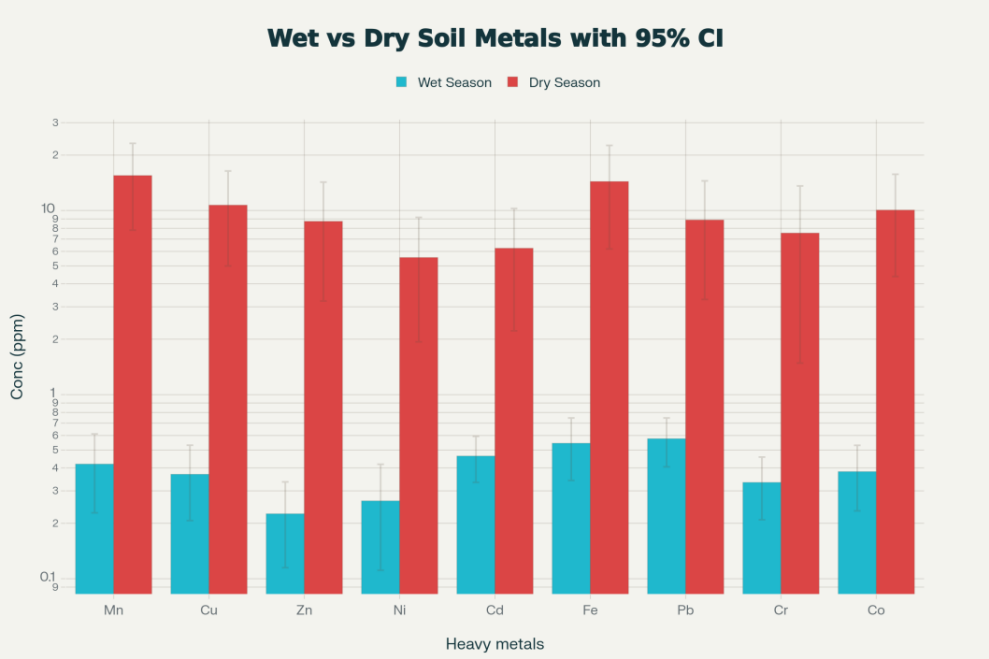


Fig O; Grouped bar chart comparing wet (blue) and dry (red) season mean soil heavy metal concentrations with 95% confidence intervals.

For all metals, dry season mean concentrations (red bars) are substantially higher than wet-season means (blue bars), and their 95% confidence intervals do not overlap in most cases, indicating strong seasonal differences in contamination levels.

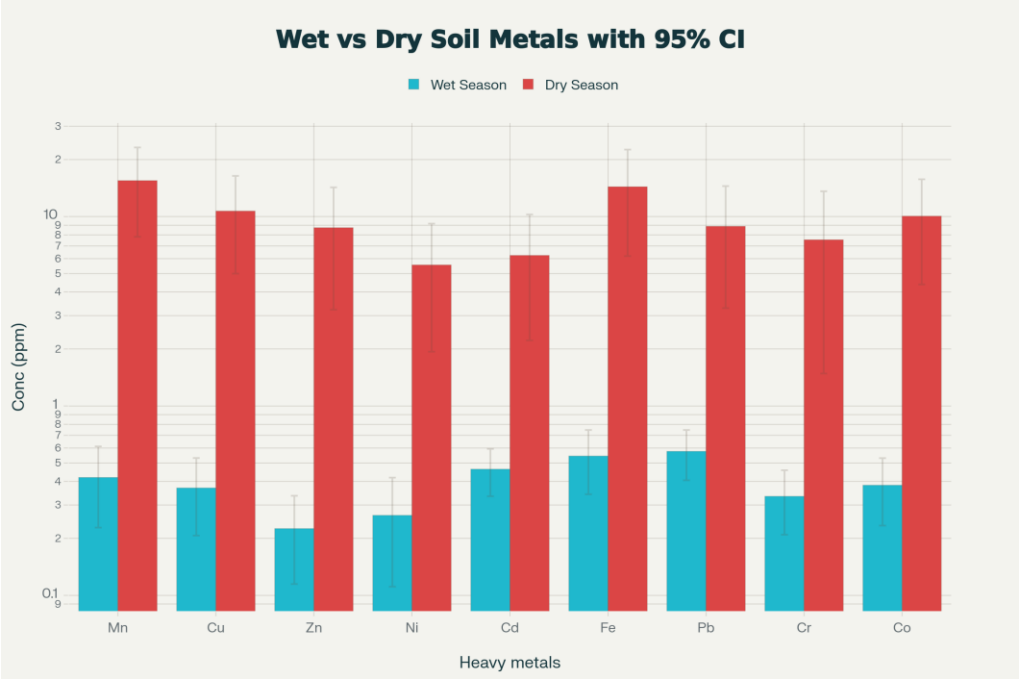


Fig P: Grouped bar chart comparing wet (blue) and dry (red) season mean soil heavy metal concentrations with 95% confidence intervals.

Dry season Fe and Mn show particularly large means and wide confidence intervals, suggesting both higher average loading and greater spatial variability in the soil during dry conditions.
Because CDI, HI, and ILCR are directly proportional to metal concentration in the exposure equations, these higher dry season concentrations imply correspondingly higher dry season risk ranges, especially for carcinogenic metals Pb, Cd, Cr, and Ni.

Propagating CI into CDI/HI/ILCR

Assuming linear proportionality between soil (or water) concentration and CDI, the 95% confidence interval bounds of concentration for Pb, Cd, Cr, and Ni define corresponding low high bounds for CDI, HI, and ILCR.
For example, if the mean ILCR for Pb in the dry season is 1.28×10^{-4}, then using the lower and upper 95% CI concentrations for Pb gives an approximate ILCR range of about half to roughly twice this central value, illustrating how sampling variability translates directly into risk uncertainty.