Multi-Metal Speciation, Phytotoxicological Assessment, and Human Health Risk Profiling of an Abandoned Lead-Acid Battery Industrial Site in Southwestern Nigeria: Implications for Sustainable Soil Remediation and Agricultural Policy

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Abstract—**Despite increasing global documentation of battery-industry soil contamination, there is a critical research gap regarding the simultaneous multi-metal speciation characterization, comparative phytotoxicological bioassay using dual crop species, and integrated probabilistic human health risk assessment at a single abandoned site in sub-Saharan Africa. This study, conducted at an abandoned lead-acid battery industrial site in Ibadan, Southwestern Nigeria, addresses this gap by integrating ICP-OES-based geochemical analysis with a structured six-week greenhouse bioassay using Celosia argentea (vegetable) and Abelmoschus esculentus (okra) as phytotoxicological bioindicators, and by applying the USEPA probabilistic risk framework across oral ingestion and dermal contact exposure pathways for both children and adults. Soil and water samples were collected from the abandoned battery site and a control location. Physicochemical parameters were determined using standard methods. Twenty-seven metallic elements were quantified by ICP-OES (Agilent 720). Plant bioassays were conducted for six weeks under greenhouse conditions using contaminated soil and site water. Human health risk (non-carcinogenic and carcinogenic) was assessed following USEPA guidelines.**

Extreme soil acidification (pH 3.98 ± 0.32) and catastrophic lead contamination (603,432.25 mg/kg, approximately 2,738× the guideline value) were detected. Physicochemical water quality exceeded WHO limits for alkalinity, chloride, and suspended solids. Complete growth inhibition was recorded in both crop species irrigated with site water, while stunted growth and chlorosis were observed in crops grown in contaminated soil. Hazard Index (HI) values for soil exposure reached 20,529,671 (adult, dermal) and 43,796,632 (child, dermal). Cancer Risk Index values for soil Pb (dermal) reached 15,840 for adults and 33,792 for children, far exceeding the USEPA acceptable limit of 1×10^{-4}. The abandoned battery site represents an acute multi-hazard environmental disaster. The dual-crop bioassay confirms species-specific differential tolerance, with Abelmoschus esculentus showing marginally superior resilience. Urgent phytoremediation and bioremediation strategies, alongside regulatory enforcement, are recommended.

Index Terms—**Lead-acid battery contamination; heavy metal phytotoxicity; ICP-OES speciation; human health risk assessment; abandoned industrial site**

I. Introduction

Industrial activities involving heavy metal-intensive processes represent one of the most persistent sources of environmental contamination globally (Nagajyoti *et al.*, 2010). Lead-acid battery manufacturing and recycling are particularly hazardous due to the incorporation of large quantities of lead (Pb), cadmium (Cd), sulfuric acid (H_2SO_4), and associated trace metals throughout the production cycle (Choudhary *et al.*, 2024). When such facilities are abandoned without adequate decommissioning or remediation, they leave behind a complex toxic legacy that can persist in soil and water systems for decades, continuing to threaten ecosystem integrity and human health (Wuana and Okieimen, 2011).

Sub-Saharan Africa presents a particularly acute context for this problem. Rapid industrialization, inadequate environmental regulation, and insufficient waste management infrastructure have allowed battery manufacturing and recycling operations to proliferate without adequate environmental safeguards (Gottesfeld *et al.*, 2018). Nigeria, as the largest economy in Africa with a substantial informal battery recycling sector, exemplifies these challenges. Yet, despite growing awareness of the problem, site-specific quantitative assessments integrating geochemical characterization, phytotoxicological experimentation, and probabilistic human health risk modelling remain scarce in the peer-reviewed literature for Nigerian contexts.

Previous studies have documented heavy metal contamination at battery sites in Africa (Gottesfeld *et al.*, 2018; Kolawole *et al.*, 2024), but these investigations have been limited by: (i) reliance on single-element or limited-panel analyses rather than comprehensive multi-element ICP-OES speciation of all twenty-seven potentially toxic metals; (ii) absence of controlled phytotoxicological bioassays using locally relevant crop species under experimental conditions; and (iii) lack of simultaneous assessment of both carcinogenic and non-carcinogenic risk indices across multiple exposure pathways and receptor age groups. Furthermore, the comparative differential tolerance of food crops specifically vegetables in the *Amaranthaceae* family versus *Malvaceae* okra at Nigerian battery contamination sites has not been experimentally demonstrated.

The present study addresses these gaps by investigating an abandoned lead-acid battery industrial site in Ibadan, Oyo State, Southwestern Nigeria. Specifically, the study: (1) provides comprehensive ICP-OES-based multi-element speciation of soil and water contaminants; (2) conducts a structured six-week greenhouse bioassay comparing the phytotoxicological responses of *Celosia argentea* and *Abelmoschus esculentus* across four treatment combinations of contaminated soil and water; (3) evaluates non-carcinogenic Hazard Index (HI) and carcinogenic Cancer Risk Index (CRI) values via both ingestion and dermal pathways for adult and child receptor populations; and (4) compares findings against international benchmark datasets to contextualise the severity of contamination. The novelty of this integrated approach is the combination of geochemical speciation, live crop bioassay, and probabilistic risk modelling at a single site that provides a methodological template applicable to similar legacy industrial sites across West Africa and beyond.

II. MATERIALS AND METHODS

2.1 Study Area Description

The study site is an abandoned lead-acid battery industrial facility located in Ibadan, Oyo State, Southwestern Nigeria (approximately 7.38°N, 3.90°E). Ibadan is the largest city by geographical area in sub-Saharan Africa and hosts a mix of formal and informal industrial operations. The battery facility ceased operations without formal site closure or remediation procedures, leaving behind significant quantities of lead plates, battery casings, sulfuric acid residues, and miscellaneous industrial waste. The surrounding area supports smallholder agricultural activities, increasing the potential for contaminated soil-food chain transfer. A control site with no history of industrial activity was selected approximately 3 km from the battery site to provide baseline comparative data.

2.2 Sample Collection

2.2.1 Soil Sampling

Composite soil samples were collected at a standardized depth of 0–10 cm from five systematically distributed points around the battery industrial site perimeter, consistent with USEPA soil sampling guidance (USEPA, 1996). Samples were homogenized, transferred to pre-cleaned polyethylene bags, sealed, labelled, and transported to the laboratory at 4°C for analysis. Corresponding control soil samples were collected from the reference site using an identical protocol.

2.2.2 Water Sampling

Water samples were collected from the creek adjacent to the battery facility, which receives surface runoff from the contaminated site. Sampling containers were pre-cleaned with 10% hydrochloric acid (HCl) and rinsed with deionized water prior to use. In situ measurements of pH and temperature were recorded at the point of collection using a calibrated multi-parameter probe. Samples were preserved according to standard protocols and transported to the laboratory within 24 hours for physicochemical and metal analysis.

2.3 Physicochemical Analysis

Both soil and water samples were analysed for a comprehensive suite of physicochemical parameters including: temperature, pH, total dissolved solids (TDS), electrical conductivity, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total hardness, total alkalinity, turbidity, chloride, and suspended solids. All analyses followed standard methods (APHA, 2017). Results were compared against World Health Organization (WHO, 2017) and Nigerian Environmental Standards and Regulation Enforcement Agency (NESREA) guidelines.

2.4 Heavy Metal Determination by ICP-OES

Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES; Agilent 720) was used for multi-element analysis of both soil and water samples. A total of 27 metallic elements were simultaneously quantified, encompassing major macronutrients (Na, K, Ca, Mg, Fe), micronutrients, and toxic trace metals (Pb, Cd, Cr, As, Ni, Co, Mn, Cu, Zn, Al, Sb, Ba, Be, B, Mo, Se, Si, Ag, Sr, Tl, Ti, V). Soil samples were subjected to acid digestion using aqua regia (HNO_3:HCl, 1:3) prior to analysis. Certified reference materials (CRM) and procedural blanks were included in each analytical batch for quality assurance. Instrument detection limits, precision (RSD <5%), and recovery rates (85–115%) were verified before sample analysis.

2.5 Phytotoxicological Bioassay

A controlled six-week greenhouse bioassay was designed to evaluate the phytotoxicological effects of contaminated soil and water on two locally cultivated food crop species: *Celosia argentea* (vegetable; *Amaranthaceae*) and *Abelmoschus esculentus* (okra; *Malvaceae*). These species were selected because they represent common dietary staples in Southwestern Nigeria, making the assessment of heavy metal impact on their growth directly relevant to food security and nutritional health.

The experimental design comprised four treatment groups for each species, with two replicates per group: (SBV/SBO) battery industry soil watered with tap water; (WBV/WBO) battery industry soil watered with site creek water; (CV/CO) control soil watered with tap water (positive control) as shown in Fig 1; and an additional observational group to capture within-treatment variability. Plants were grown in standardized 5-litre pots under ambient greenhouse conditions (mean temperature 28 ± 2°C; relative humidity 65 ± 5%). Weekly observations were recorded for germination status, shoot height, leaf count, leaf morphology, colour changes, root development, and reproductive output (fruit/seed formation). Shoot height was measured using a calibrated ruler, and leaf count was conducted manually at the same time each week.

Fig. 1 Plant arrangement

2.6 Human Health Risk Assessment

2.6.1 Chronic Daily Intake (CDI)

Human health risk assessment was performed following the USEPA Risk Assessment Guidance for Superfund (RAGS) framework (USEPA, 1989; 2009). Chronic Daily Intake (CDI) was calculated for both ingestion and dermal contact exposure pathways using Equations 1 and 2 respectively:

$$CDIing = (C \times IR \times EF \times ED) / (BW \times AT) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$CDIderm = (C \times SA \times AF \times ABF \times EF \times ED) / (BW \times AT) \quad \ldots(2)$$

Where C = contaminant concentration (mg/l or mg/kg), IR = ingestion rate, EF = exposure frequency (days/year), ED = exposure duration (years), BW = body weight (kg), AT = averaging time (days), SA = skin surface area (cm²), AF = adherence factor (mg/cm²), and ABF = dermal absorption factor. Exposure parameters used for adult and paediatric receptors are presented in Table 1.

Table 1. Exposure Parameters Used in Human Health Risk Assessment

Parameters (Unit)	Values
Concentration (mg/L)	Heavy Metal Values
Ingestion Rate – Adult (L/day)	2.2
Ingestion Rate – Children (L/day)	1.0
Exposure Frequency (days/year)	365
Exposure Duration – Adult (years)	30
Exposure Duration – Children (years)	6
Body Weight – Adult (kg)	70
Body Weight – Children (kg)	15
Average Time – Adult (days)	10,950
Average Time – Children (days)	2,190
Surface Area – Adult (cm²)	17,500
Surface Area – Children (cm²)	2,800
Adherence Factor – Adult (mg/cm²)	0.07
Adherence Factor – Children (mg/cm²)	0.2
Absorption Factor	0.001

Table 2. Reference Dose (RfD) and Cancer Slope Factor (SF) for Heavy Metals

Metal	RfDing	RfDderm	SFing	SFderm
Pb	3.5×10^{-3}	5.25×10^{-4}	0.0085	1.5
Cd	1×10^{-3}	1×10^{-5}	6.1	6.1
Cr	3×10^{-3}	6×10^{-5}	0.5	20
As	3×10^{-4}	1.23×10^{-4}	1.5	3.66
Cu	4×10^{-2}	1.2×10^{-2}	—	—
Zn	3×10^{-1}	6×10^{-2}	—	—
Fe	7×10^{-1}	—	—	—
Ni	2×10^{-2}	5.4×10^{-3}	—	—
Mn	1.4×10^{-1}	1.84×10^{-3}	—	—
Co	2×10^{-2}	2.1×10^{-5}	—	—

2.6.2 Non-Carcinogenic Risk

Non-carcinogenic risk was assessed using the Hazard Quotient (HQ) and Hazard Index (HI) as defined in Equations 3 and 4:

$$HQ = CDI / RfD \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

$$HI = \Sigma HQ \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

An HQ or HI value exceeding 1.0 indicates a probability of adverse non-carcinogenic health effects, with risk increasing proportionally with HI magnitude (USEPA, 2009; Jonah and Mendie, 2024).

2.6.3 Carcinogenic Risk

Carcinogenic risk was estimated for metals with established cancer slope factors (Pb, Cd, Cr, As) using Equation 5:

$$CRI = CDI \times SF \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

USEPA defines acceptable carcinogenic risk within the range of 1×10^{-6} to 1×10^{-4}. CRI values exceeding 1×10^{-4} indicate unacceptable carcinogenic risk requiring regulatory intervention.

III. RESULTS AND DISCUSSION

The physicochemical analysis of both water (Table 3) and soil (Table 4) samples revealed severe environmental degradation at the abandoned battery site, with multiple parameters exceeding regulatory guideline values.

Table 3. Physicochemical Parameters of Water Samples from Battery Site and Control Location

Parameter	Control	Battery Site	WHO Limit
pH	7.99 ± 0.01	3.98 ± 0.32	6.5–8.5
Temperature (°C)	26.3 ± 0.2	27.1 ± 0.4	≤30
Turbidity (NTU)	1.07 ± 0.05	4.91 ± 3.78	5
Alkalinity (mg/L)	51.04 ± 0.08	2333.77 ± 282.86	200
Hardness (mg/L)	71.04 ± 0.42	75.64 ± 0.03	500
TDS (ppm)	210.67 ± 0.47	192.47 ± 5.94	1000
Chloride (mg/L)	0.77 ± 0.05	3933.64 ± 1354.39	250
Conductivity (µS/cm)	631.5 ± 0.82	83.27 ± 0.21	600
COD (mg/L)	6.18 ± 0.11	1.86 ± 0.2	255
BOD (mg/L)	4.23 ± 0.00	7.60 ± 4.85	10
Suspended Solids (mg/L)	4.42 ± 0.02	891.6 ± 265.96	10
DO (mg/L)	4.81 ± 0.12	0.151 ± 0	5

Table 4. Physicochemical Parameters of Soil Samples from Battery Site and Control Location

Parameter	Control (mg/kg)	Battery Site (mg/kg)	Standard (mg/kg)
Iron (Fe)	1.25 ± 0.08	1.53 ± 0.30	0.1
Sodium (Na)	—	0.35 ± 0.14	200
Calcium (Ca)	5.00 ± 0.01	4.13 ± 1.49	200
Potassium (K)	0.20 ± 0.01	0.53 ± 0.18	N/A
Magnesium (Mg)	—	0.82 ± 0.29	N/A
Copper (Cu)	—	0.17 ± 1.00	0.5
Zinc (Zn)	—	0.62 ± 1.00	5
Lead (Pb)	—	0.09 ± 0.01	0.01
Chromium (Cr)	—	0.12 ± 0.05	0.05

The soil pH at the contaminated site (3.98 ± 0.32) was dramatically reduced compared to the control (7.99 ± 0.01), representing a decrease of approximately 4 pH units. This extreme acidification is primarily attributable to sulfuric acid electrolyte leaching from discarded lead-acid batteries, which typically contain 17–22% diluted H_2SO_4 by weight (Choudhary *et al*., 2024). Similar acidification has been documented at battery recycling sites in West Africa, though values below pH 4.0 are exceptionally rare and represent a worst-case contamination scenario (Kolawole *et al*., 2024). At pH 3.98, the solubility of heavy metals including Pb, Al, Mn, and Fe is dramatically increased, significantly enhancing phytotoxic bioavailability (Angulo-Bejarano *et al*., 2021).

Water quality was severely compromised across multiple parameters. Dissolved oxygen (DO) at the battery site (0.151 ± 0 mg/l) was 97% below the WHO standard of 5 mg/L and control value (4.81 ± 0.12 mg/l), indicating near-complete oxygen depletion and severe aquatic ecosystem degradation (Badeenezhad *et al.*, 2023). The extraordinary alkalinity (2333.77 ± 282.86 mg/l, exceeding the WHO limit of 200 mg/l by over 10-fold) in water adjacent to the strongly acidified soil reflects complex hydrogeochemical buffering reactions involving dissolved carbonates and metal hydroxide precipitation. Chloride content (3933.64 ± 1354.39 mg/l) similarly exceeded guideline values, with implications for osmotic stress in irrigation-dependent crops. Suspended solids (891.6 ± 265.96 mg/l) were 89 times above the WHO limit of 10 mg/l, further degrading water quality and reducing light penetration in the associated water body.

3.2 Heavy Metal Contamination Profile and Multi-Element Speciation

ICP-OES analysis revealed a complex poly-metallic contamination signature at the battery site, with concentrations of most metals dramatically exceeding WHO, NESREA, and EU soil quality guideline values. Lead (Pb) was the dominant contaminant in soil at 603,432.25 mg/kg, representing a 2,738-fold exceedance of the standard value (220.35 mg/kg). This is consistent with the primary role of Pb in lead-acid battery chemistry, where each battery contains approximately 12–20 kg of Pb by weight (Choudhary *et al.*, 2024). Additional significant soil contaminants included iron (Fe: 263,424.69 mg/kg), aluminum (Al: 109,123.43 mg/kg), antimony (Sb: 12,123.87 mg/kg), manganese (Mn: 3,635.10 mg/kg), copper (Cu: 1,215.65 mg/kg), and chromium (Cr: 424.79 mg/kg).

Table 5 contextualizes the findings of this study against comparable contamination data from battery sites globally. The Pb concentration at the study site exceeds documented values from other African battery sites by approximately 50-fold (Kolawole *et al.*, 2024), and exceeds values from smelting-affected soils in China and India by similar magnitudes (Adnan et al., 2024). This position the Ibadan battery site among the most severely Pb-contaminated agricultural land matrices documented in the peer-reviewed literature.

Table 5. Comparative Lead Contamination Levels at Battery and Smelting Sites Globally

Study Location	Pb (mg/kg)	Cd (mg/kg)	pH	Reference
This Study (Ibadan, Nigeria)	603,432	Detected	3.98	Present study
Battery recycling, Africa	2,600–12,000	0.5–15	4.2–5.8	Kolawole *et al.*, 2024
Smelting sites, China	500–50,000	1–200	4.5–6.5	Adnan *et al.*, 2024
Lead-acid battery sites, India	1,200–8,000	0.3–12	4.8–6.0	Choudhary *et al.*, 2024
WHO/EU Guideline	≤85	≤3	6.5–8.5	WHO 2007

The poly-metallic contamination profile with simultaneous exceedances for Pb, Al, Sb, Cr, Cu, Mn, and Na, creates synergistic toxicological conditions more severe than single-metal contamination scenarios. Research has demonstrated that metal mixture toxicity frequently exceeds the sum of individual metal effects due to shared physiological targets (El-Sappah et al., 2024). The non-biodegradable nature of these metals ensures persistent environmental contamination, creating a chronic reservoir of phytotoxicity absent active remediation intervention.

3.3 Phytotoxicological Bioassay: Differential Crop Responses

The six-week greenhouse bioassay revealed distinct and species-specific phytotoxicological responses across treatment groups (Table 6). Detailed weekly observations are summarized below:

Table 6. Weekly Phytotoxicological Observations for *Celosia argentea* and *Abelmoschus esculentus* across Treatment Groups

Week	C-V / C-O (Control)	S+V / S+O (Battery Soil + Tap Water)	W+V / W+O (Battery Soil + Site Water)	Key Observation
1	Germination confirmed; 8 cm height (Okra)	Vegetable germinates; Okra: no germination	No germination in any species	Heavy metal inhibition at seed stage
2	Root/stem/leaf elongation; vigorous	Thin stems, narrow leaves; slow progress	Still no germination	Delayed meristematic activity
3	>4 leaves (Veg); 4 leaves (Okra)	4 leaves (Veg); Okra germinates	No change	Differential species tolerance emerging
4	Vigorous; 6 leaves (Okra); broad leaves	4 leaves (Veg); limited Okra leaf expansion	No change	Growth suppression intensifying
5	Seed appearance (Veg); fruit (Okra); 8 leaves	Chlorosis (Veg yellowing); 3 Okra leaves	No change	Chlorophyll degradation in treatment group
6	>20 leaves; pink seed (Celosia); 10+ leaves; 6 fruits (Okra); 16 inches	Leaf deterioration (Veg); fruit appears (Okra); 9 inches	No observable growth in either species	Complete growth failure under heavy metal stress

3.3.1 *Celosia argentea* (Vegetable) Response

Control plants (C-V) exhibited vigorous, unimpeded growth throughout the six-week period, achieving over 20 leaves by Week 6 with characteristic pink seed development shows a phenotypic marker of reproductive maturity in *Celosia argentea*. Plants grown in battery-contaminated soil but irrigated with tap water (S+V) germinated normally but demonstrated progressively restricted growth, culminating in chlorosis (leaf yellowing) by Week 5 and complete failure to achieve reproductive maturity by experiment termination. Plants subjected to both contaminated soil and contaminated site water (W+V) showed total growth inhibition with no germination recorded throughout the six-week experimental period.

3.3.2 *Abelmoschus esculentus* (Okra) Response

Control okra plants (C-O) achieved a shoot height of 16 inches and produced 6 fruits by Week 6, with leaf dimensions of 6 inches shows consistent with normal agronomic performance for this species under Nigerian conditions. Plants in the contaminated soil with tap water treatment (S+O) exhibited delayed germination (first observed Week 4) and significantly stunted growth, achieving only 9 inches shoot height by Week 6 without fruit production. Critically, plants subjected to contaminated site water irrigation (W+O) showed complete growth failure with no germination was observed at any point during the six-week experimental period, consistent with the severe toxicity of the site water (DO = 0.151 mg/l; Pb at extreme concentrations).

3.3.3 Comparative Phytotoxicological Interpretation

The differential responses between species are noteworthy and constitute a novel contribution of this study. *Abelmoschus esculentus* demonstrated marginally superior resilience to battery-contaminated soil conditions compared to *Celosia argentea*, with okra plants in contaminated soil (S+O) achieving delayed but measurable germination, stem elongation, and fruit development by Week 6. This differential tolerance may reflect species-specific cell wall characteristics, metal exclusion mechanisms at the root apoplast, or differences in antioxidant enzyme capacity (El-Sappah *et al*., 2024). The observed chlorosis in Celosia argentea (S+V) is consistent with copper and zinc-mediated disruption of chlorophyll biosynthesis, wherein these metals competitively inhibit magnesium incorporation into the porphyrin ring (Kabata-Pendias, 2010).

The complete growth inhibition observed across both species in the W+V and W+O groups, despite differing species-level tolerances, underscores the catastrophic phytotoxic potential of the site water. The virtually absent dissolved oxygen (0.151 mg/l) indicating insufficient to support root aerobic respiration which was combined with extreme Pb, Cr, and Al concentrations would simultaneously disrupt membrane integrity, enzyme function, photosystem II efficiency, and stomatal conductance (Singh *et al*., 2015; Kanwal *et al*., 2024). These findings have direct implications for food security for both *Celosia argentea* and *Abelmoschus esculentus* are commercially cultivated in per urban agricultural zones in Ibadan, and their failure to produce viable crops in contaminated media confirms that continued agricultural use of contaminated land without remediation constitutes an unacceptable risk to the food supply chain.

3.4 Non-Carcinogenic Health Risk Assessment

Non-carcinogenic risk from heavy metal exposure in water samples is presented in Table 7, and corresponding data for the combined water and soil exposure scenario is presented in Table 8.

Table 7. Non-Carcinogenic Risk (HQ and HI) for Water Sample Exposure in Adult and Paediatric Receptors

Metal	CDIing Adult	CDIderm Adult	HQing Adult	HQderm Adult	CDIing Child	CDIderm Child	HQing Child	HQderm Child
Pb	0.0028	0.0016	0.808	3.000	0.0060	0.0034	1.714	6.400
Cr	0.0038	0.0021	1.257	35.00	0.0080	0.0045	2.667	74.67
Cu	0.0053	0.0030	0.134	0.248	0.0113	0.0063	0.283	0.529
Zn	0.0195	0.0109	0.065	0.181	0.0413	0.0231	0.138	0.386
Fe	0.0481	0.0268	0.069	—	0.1020	0.0571	0.146	—
HI			2.333	38.43			4.948	81.98

For water-only exposure, the Hazard Index (HI) exceeded the safe threshold of HI < 1 for both adults (HI = 2.33 via ingestion; 38.43 via dermal contact) and children (HI = 4.95 via ingestion; 81.98 via dermal contact), confirming substantial non-carcinogenic risk from water exposure alone. Chromium contributed the highest individual HQ values (35.0 for adults; 74.67 for children via dermal contact), reflecting both its toxicological potency and its dermal absorption characteristics.

When soil exposure is incorporated, risk magnitudes increase catastrophically. Adult HI values reach 5,539,953 (ingestion) and 20,529,671 (dermal), while pediatric HI values reach 3,084,746 (ingestion) and 43,796,632 (dermal). These values exceed the safe threshold by factors of 10^6–10^7, reflecting the extreme heavy metal loading in the soil matrix. Lead, arsenic, and chromium were identified as the dominant contributors to non-carcinogenic risk across both exposure pathways. The consistently elevated HI in children compared to adults across all pathways reflects the well-established physiological vulnerability of paediatric receptors: higher surface area-to-bodyweight ratio, greater hand-to-mouth behaviour, and more susceptible developing organ systems (Al Osman *et al*., 2019; Dietert and Piepenbrink, 2006).

3.5 Carcinogenic Risk Assessment

Cancer Risk Index (CRI) values for water and soil exposure are presented in Table 8.

Table 8. Cancer Risk Index (CRI) via Ingestion and Dermal Exposure Routes in Water and Soil Samples

Metal	CRIing Adult	CRIderm Adult	CRIing Child	CRIderm Child
Pb	0.000024	0.002363	0.000051	0.005040
Cr	0.001886	0.042000	0.004000	0.089600

For water exposure, ingestion-route CRI values for lead remained within the USEPA acceptable range (1×10^{-6} to 1×10^{-4}) for both adults (8.01×10^{-6}) and children (4.46×10^{-6}). However, dermal contact CRI for lead (0.00079 adults; 0.00168 children) and all chromium exposure pathways substantially exceeded acceptable thresholds. This finding highlights the critical importance of dermal exposure assessment in settings where direct soil and water contact is common showing a scenario of typical smallholder farmers in the study area who may work barefoot in contaminated fields.

Soil CRI values exceeded the USEPA acceptable limit by several orders of magnitude across all carcinogenic metals and exposure pathways. Lead soil CRI via dermal contact reached 15,840 for adults and 33,792 for children with values approximately 1.6×10^{8} and 3.4×10^{8} times above the acceptable upper limit of 1×10^{-4} respectively. These extraordinary values are a function of the extreme soil Pb concentration (603,432 mg/kg) and confirm that the site constitutes an acute carcinogenic risk requiring immediate access restriction. Children face consistently higher CRI values than adults across all pathways, reflecting their greater exposure susceptibility and longer remaining lifetime for cancer development (Badeenezhad *et al.*, 2023).

The carcinogenic risk associated with chromium at this site warrants specific attention. Chromium (VI), which is the primary carcinogenic species from industrial emissions, has well-documented associations with lung cancer through inhalation and with gastrointestinal malignancies through ingestion (Li *et al.*, 2022). The high soil Cr concentration (424.79 mg/kg) and elevated CRI values reinforce the need for speciation-resolved Cr analysis which distinguishing Cr (III) from Cr (VI) in future monitoring studies at this site, as this distinction has direct implications for remediation target-setting and risk communication.

3.6 Remediation Recommendations and Policy Implications

The findings of this study have immediate and long-term implications for environmental management. In the near term, complete exclusion of the contaminated site perimeter from agricultural use is non-negotiable, given the demonstrated failure of both crop species and the catastrophic human health risk indices. Warning signage, community notification, and engagement with local agricultural extension services should be initiated immediately.

For medium-term remediation, a phased approach is recommended: (i) electrokinetic remediation to mobilizes and extract Pb and Cr from the highly contaminated soil matrix (Acosta Hernández et al., 2023; 2024); (ii) application of biochar or zero-valent iron nanoparticles to immobilize residual heavy metals and raise soil pH toward the target range of 6.0–7.0 (Liu et al., 2020); (iii) bioleaching using indigenous sulfur-oxidizing and metal-tolerant bacteria to enhance metal solubilization and subsequent extraction

(Hama Aziz *et al*., 2023); and (iv) subsequent phytoremediation trials using metal hyperaccumulators such as *Helianthus annuus* (sunflower) or *Thlaspi caerulescens*, supplemented with biodegradable chelating agents, once soil pH has been elevated to levels compatible with plant establishment (Chen *et al*., 2020; Gong *et al*., 2020).

At the policy level, this study contributes empirical evidence in support of mandatory environmental site assessments prior to industrial abandonment, a requirement currently absent or unenforced in the Nigerian regulatory framework. The establishment of a national registry of legacy contamination sites, modelled on the New York State Department of Health heavy metals registry (NYSDOH, 2024), would enable systematic prioritization of remediation resources. Furthermore, the rapid global expansion of lead-acid battery demand that driven by conventional automotive applications and complemented by lithium-ion demand from electric vehicle adoption (Lee et al., 2025) which makes the development of robust end-of-life battery management frameworks increasingly urgent, not only for Nigeria but for all industrializing economies.

IV. CONCLUSION

This study presents, the first integrated multi-element ICP-OES geochemical characterization, controlled dual-crop phytotoxicological bioassay, and probabilistic human health risk assessment conducted at an abandoned lead-acid battery industrial site in Southwestern Nigeria. The findings document catastrophic environmental contamination of soil Pb concentrations of 603,432 mg/kg (2,738× guideline), soil pH of 3.98, and water DO of 0.151 mg/l collectively create a phytotoxic environment that resulted in complete growth inhibition of both *Celosia argentea* and *Abelmoschus esculentus* when exposed to site water, and severely stunted growth when grown in contaminated soil.

The novel finding that *Abelmoschus esculentus* exhibits marginally superior phytotoxicological resilience compared to *Celosia argentea* in battery-contaminated soil provides crop-specific information relevant to agricultural risk management in contaminated periurban environments. However, neither species is capable of sustained productive growth under the contamination conditions documented at this site.

Human health risk modelling confirms that both non-carcinogenic (HI up to 4.38×10^7 for children via soil dermal contact) and carcinogenic (CRI up to 3.38×10^4 for children via soil Pb dermal contact) risks far exceed acceptable limits. Children represent the most vulnerable receptor population at this site. The findings provide a robust scientific basis for: (i) immediate site exclusion from agricultural use; (ii) priority remediation using electrokinetic and bioremediation approaches; and (iii) policy reforms requiring mandatory environmental liability assessments and post-industrial site monitoring in Nigeria.

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