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Heavy Metal Contamination in Plants associated with Battery Waste Disposal at a Recycling Site in Ogun State, South-western Nigeria

Adeniyi T. Adeleke[1,2], Rasaki Kola Odunaike[1], Mistura T. Adeleke[3], Oladapo H. Ajiboye[4]
Kafila T. Oyebisi[5], Sherifat O. Ayinla[2]

1. Department of Physics, OOU, Ago-Iwoye, Ogun State, Nigeria.
2. Department of Science Laboratory Technology, Federal College of Fisheries and Marine Technology, Victoria Island, Lagos.
3. Department of Zoology, Ago-Iwoye, Ogun State, Nigeria.
4. Department of Mathematical and Computing Science, Koladaisi University Ibadan, Oyo State.
5. Department of Biological Sciences, Lagos State University of Science and Technology, Ikorodu, Lagos.

Corresponding Author: Adeniyi T. Adeleke; adeleke@fcfmt.edu.ng

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ABSTRACT

Uncontrolled disposal and informal recycling of used lead-acid batteries are major sources of heavy metal contamination in peri-urban soils and food crops in Nigeria. This study quantified the bioaccumulation and health risks of nine metals (Mn, Fe, Cu, Zn, Pb, Co, Cd, Cr and Ni) in edible plants cultivated around a battery recycling site in Ogijo, Ogun State. During wet and dry seasons, randomly selected plants and paired soil samples were digested and analyzed using atomic absorption spectrometry; bioaccumulation factor (BAF), Metal Accumulation Index (MAI) and Health Risk Index (HRI) were used to assess soil-to-plant transfer, multi-metal accumulation and non-carcinogenic dietary risk. Concentrations of Zn, Cd, Pb, Cr and Co in all plant species exceeded FAO/WHO guideline values for vegetables in both seasons, with higher levels generally recorded in the dry season. MAI values showed severe multi-metal stress in all species, especially maize (*Zea mays*), cassava leaves (*Manihot esculenta*), cocoyam leaves (*Xanthosoma sagittifolium*) and spinach (*Spinacia oleracea*). BAF values for Cd, Pb and Zn were mostly below 1.0 in the wet season but exceeded 1.0 in several dry-season cases, confirming efficient transfer under low-moisture conditions. HRI values for Cd and Pb in cassava leaves, spinach and ewedu (*Corchorus olitorius*) far exceeded 1.0, indicating unacceptable dietary risks. In general, the study area is unsuitable for food-crop production underscoring the need for stricter control, relocation and remediation of battery recycling activities.

Keywords: heavy metals, battery recycling, health risk index, bioaccumulation factor and metal accumulation index

INTRODUCTION

Heavy metal pollution in soils is becoming increasingly widespread as a result of intensified industrialization, urbanization and agricultural activities. Globally, uncontrolled dumping of urban waste, mining operations, and the frequent use of agrochemicals such as herbicides, insecticides and fungicides have contributed substantially to the accumulation of potentially toxic metals in agricultural soils. Heavy metals in soil threaten the health of humans, animals and plants and are among the most persistent contaminants in terrestrial and aquatic environments. Their toxicity is of growing concern from ecological, evolutionary, nutritional and environmental perspectives.

Cadmium, copper, lead, chromium, manganese, iron and mercury are among the most harmful heavy metals in terrestrial ecosystems, particularly in areas subjected to high anthropogenic pressure. The accumulation of heavy metals in soil undermines agricultural productivity by reducing food safety, marketability and crop yield. At the plant level, excessive metal concentrations can adversely affect biomass production, photosynthetic activity, stomatal characteristics, transpiration rate, nutrient uptake, ATPase activity and can induce necrosis and chlorosis (Gul *et al.*, 2019). Unlike many organic pollutants, heavy metals do not degrade and can persist in soils for long periods; at elevated or non-essential concentrations, they pose chronic risks to biota. These metals may occur naturally in parent materials but often become highly enriched through human activities in the surrounding environment. Once inhaled, ingested or absorbed through plant and animal tissues, they can bind to and interfere with key cellular components and biochemical processes.

Plants are vital components of ecosystems because they mediate the transfer of materials from abiotic compartments such as soil, water and atmosphere into the biotic food web (Martínez-López *et al.*, 2014). The primary source of trace elements for plants is their growth medium, but atmospheric deposition can also make an important contribution. Positive relationships between atmospheric heavy metal deposition and metal concentrations in plant tissues have been reported in several studies (Kleckerová & Dočekalová, 2014; Hu *et al.*, 2014). Plants take up and transport heavy metals both through their root systems and across exposed surfaces, especially leaves, making it difficult in many field environments to distinguish the relative contributions of soil and air pathways (Hu *et al.*, 2014). Heavy metal contamination of agricultural soils is therefore a major environmental issue, as these substances are prevalent and can exert both immediate and long-term adverse effects on crops and associated ecosystems. Plants growing in contaminated environments typically exhibit much higher metal concentrations than those in relatively pristine areas. The uptake and accumulation of heavy metals by plants depend on plant species, soil physical and chemical properties, temperature and rainfall patterns.

In Nigeria, informal recycling and uncontrolled disposal of used lead-acid batteries have emerged as significant sources of heavy metal pollution in peri-urban soils and food crops, particularly where recycling activities occur close to residential areas and subsistence farmlands. Ogijo, in Ogun State, southwestern Nigeria, hosts a spent battery recycling facility surrounded by smallholder agricultural plots where commonly consumed food crops are cultivated. Systematic assessment of metal contamination in soils and edible plant tissues in such settings is essential for understanding exposure pathways and potential health risks to local populations.

This study therefore aimed to:

(i) quantify seasonal concentrations of heavy metals (Mn, Fe, Cu, Zn, Pb, Co, Cd, Cr and Ni) in edible plants grown around a spent battery recycling site in Ogijo;
(ii) evaluate soil-plant transfer and multi-metal accumulation using the bioaccumulation factor (BAF) and Metal Accumulation Index (MAI); and
(iii) assess non-carcinogenic dietary risk to local consumers using the Health Risk Index (HRI) based on established USEPA/WHO toxicological guidance.

These objectives are intended to provide an evidence base for local and national regulators, as well as for communities, to design appropriate control and remediation measures for battery recycling activities in agricultural landscapes.

MATERIALS AND METHODS

Study location, sample collection, preparation, and analysis

The study was conducted at a spent battery recycling site in Ogijo, Sagamu Local Government Area, Ogun State, southwestern Nigeria (6°50′54.60″ N, 3°38′46.79″ E). The area lies within a tropical climatic zone characterized by distinct wet and dry seasons and is surrounded by residential buildings and subsistence agricultural plots. Figure 1 shows the location of the facility and the approximate sampling points.

Soil and edible plant samples were collected during the wet season (August) and the dry season (February). Six commonly cultivated food plant species were sampled during the wet season: A, maize (*Zea mays*); B, cassava leaves (*Manihot esculenta*); C, cocoyam leaves (*Xanthosoma sagittifolium*); D, spinach (*Spinacia oleracea*); E, ewedu (*Corchorus olitorius*); and F, scent leaf (*Ocimum gratissimum*). During the dry season, only species A–D were available for sampling because species E and F were absent, possibly as a result of drought stress and/or heavy metal phytotoxicity.

At each sampling point, soil and corresponding plant samples were collected in triplicate. Surface soil samples were collected from the root zone, while edible plant tissues were harvested from the same locations to allow soil-plant comparison. For leafy vegetables, leaves and tender shoots were collected, whereas the edible above-ground tissue was sampled for maize. All samples were placed in acid-washed polyethylene bags, transported to the laboratory, air-dried at 40 °C for 72 h, ground, sieved to a particle size < 2mm and stored in clean sealed containers until analysis (APHA, 2005).

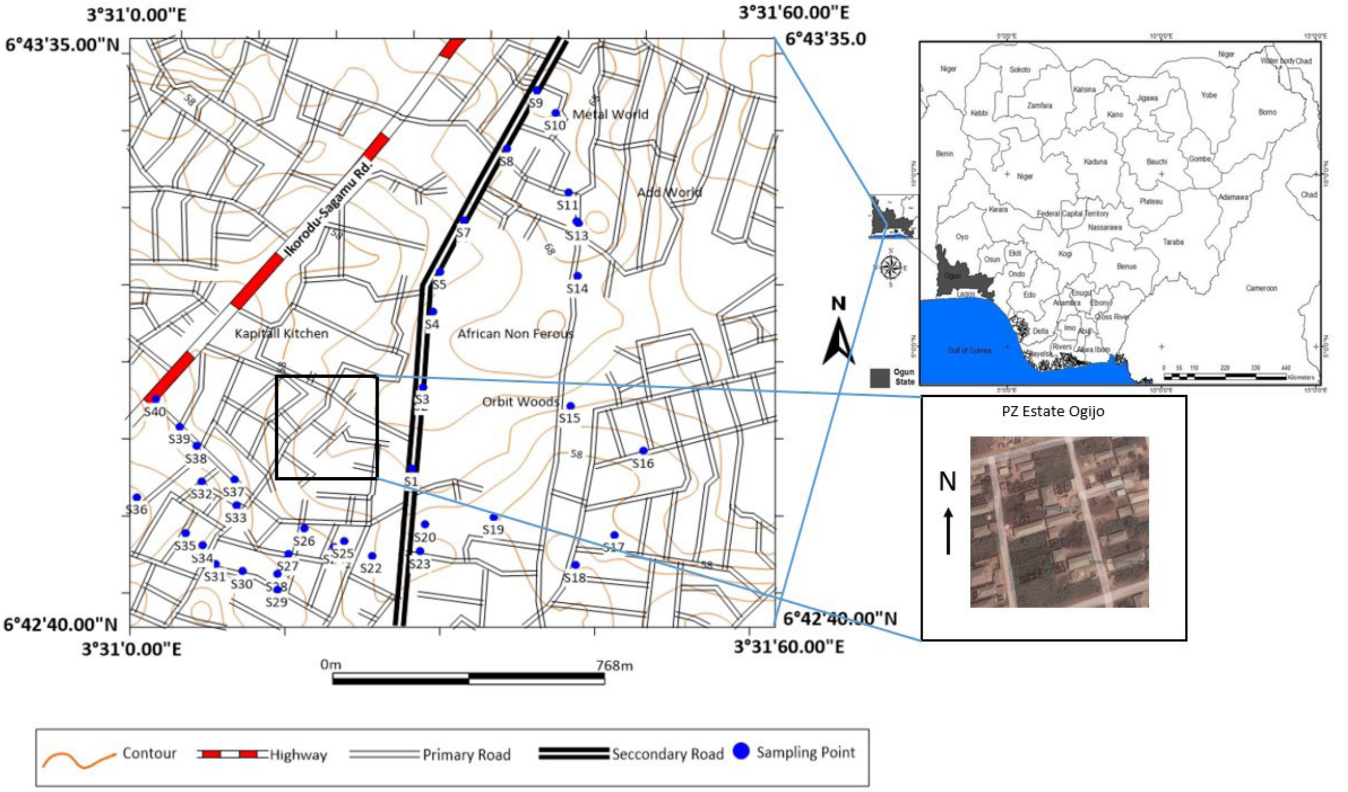

Figure 1: Map of Nigeria showing the location of sample collection places around the battery recycling facility in Ogijo, Ogun State.

Sample Digestion and Elemental Analysis

Two subsamples of 0.5 g were taken from each dried plant sample and digested following standard procedures (Awofolu *et al.*, 2005). Each subsample was weighed into a 100 mL borosilicate beaker and treated with 5 mL of concentrated HNO_3 and 2 mL of $HClO_4$. The mixture was heated on a hot plate at 70 °C for 15 min until a clear, light-coloured solution was obtained. After cooling, the digest was filtered through Whatman No. 42 filter paper and diluted to 25 mL with deionized water.

Metal concentrations were determined using flame atomic absorption spectrophotometry (FAAS) with a PG-990 instrument. Multi-element standard solutions prepared from 1000 mg/L stock solutions were used for calibration within a 0–10 mg/L working range. Instrument calibration was verified daily, and analytical quality control was maintained using duplicate samples representing 10% of the total number of samples. Percentage recoveries ranged from 92% to 108%, while coefficients of variation were below 5%, indicating acceptable analytical precision and accuracy.

Metal Accumulation Index (MAI)

Environmental contamination by multiple heavy metals is common, and interactions among metals can produce combined toxic effects that differ from those of individual pollutants (Hu *et al.*, 2014). To evaluate the overall accumulation of multiple metals in plant tissues, the Metal Accumulation Index (MAI) was calculated according to Liu *et al.* (2007) and Monfared *et al.* (2013). The MAI was computed as:

$$MAI = \frac{1}{N}\sum_{j=1}^{N} I_j \quad (1)$$

where N is the total number of analysed metals and I_j is the sub-index for metal j. The sub-index was defined as:

$$I_j = \frac{x_j}{\delta x_j} \quad (2)$$

where x_j is the mean concentration of metal j in the plant sample and δx_j is the corresponding standard deviation.

Bioaccumulation factor (BAF)

The bioaccumulation factor (BAF) was used to quantify soil-to-plant transfer efficiency for each metal. It was defined as the ratio of the metal concentration in the edible plant tissue to the corresponding concentration in the associated soil sample from the same site and season:

$$BAF = \frac{C_{plant}}{C_{soil}} \quad (3)$$

where C_{plant} is the concentration of the metal in the plant tissue (mg/kg dry weight) and C_{soil} is the concentration of the metal in the associated soil sample (mg/kg dry weight).

Health Risk Index (HRI)

The Health Risk Index (HRI) was used to assess non-carcinogenic dietary risk resulting from the consumption of contaminated vegetables. First, the estimated daily intake (EDI) of each metal was calculated as:

$$EDI = \frac{C_{plant} \times DI}{BW} \quad (4)$$

where DI is the daily ingestion rate of vegetables (kg/day) and BW is the average body weight (kg). The HRI was then calculated as:

$$HRI = \frac{EDI}{RfD} \quad (5)$$

where RfD is the oral reference dose for the metal. Values of HRI < 1 were interpreted as indicating negligible non-carcinogenic risk, whereas HRI ≥ 1 was taken to indicate potential health concern, in line with USEPA/WHO toxicological guidance.

Statistical tools

The statistical analysis in this study was based on simple descriptive, index-based tools that are standard in heavy metal bioaccumulation and risk studies. Descriptive statistics were first applied to all soil and plant data; for each metal, plant species and season, the arithmetic mean and standard deviation were calculated to summarize central tendency and variability. These mean and SD values were then used directly in the indices described below.

Three quantitative indices were finally employed. The bioaccumulation factor (BAF) was calculated for each metal as the ratio of its concentration in the edible plant tissue to its concentration in the corresponding soil, providing a simple measure of soil-to-plant transfer efficiency. The Metal Accumulation Index (MAI) combined the mean and standard deviation of all metals to give a single multi-metal accumulation score for each plant, following the approach of Liu *et al.* (2007) and Monfared *et al.* (2013). The Health Risk Index (HRI) was used to estimate non-carcinogenic dietary risk based on metal concentration, vegetable intake, body weight and reference dose. HRI values greater than 1 were considered indicative of potential health risk.

RESULTS AND DISCUSSIONS

Heavy metal contamination in plant tissues

Table 1 shows the concentrations of heavy metals accumulated in plant tissues collected from the study site during the wet and dry seasons. The absence of plants E (*Corchorus olitorius*) and F (*Ocimum gratissimum*) during the dry season may be related to drought stress and/or the phytotoxic effects of elevated heavy metal concentrations at the site. The concentrations of Zn, Cd, Pb, Cr and Co in many of the sampled plants exceeded the WHO guideline values shown in Table 1. Manganese concentrations were generally higher in the dry season than in the wet season, but remained below the agronomic sufficiency range of 20–40 mg/kg reported for plant tissues by Sela (2023), and also below the health-based reference value shown in Table 1.

Table 1 further reveals the mean concentrations of nine heavy metals (Mn, Cu, Zn, Ni, Cd, Fe, Pb, Cr and Co) in edible plant tissues of six commonly consumed crop species around the battery recycling site. The sampled plants were maize (*Zea mays*), cassava leaves (*Manihot esculenta*), cocoyam leaves (*Xanthosoma sagittifolium*), spinach (*Spinacia oleracea*), ewedu (*Corchorus olitorius*) and scent leaf (*Ocimum gratissimum*), all of which form part of local diets in southwestern Nigeria.

In the wet season, concentrations of Zn, Cd, Pb, Cr and Co in most species exceeded WHO/FAO-based guideline limits for vegetables, indicating substantial contamination of edible biomass. For example, cassava leaves (*M. esculenta*) contained 5.65 mg/kg Zn and 5.05 mg/kg Cd, compared with recommended maximum values of about 0.6 mg/kg and 0.02 mg/kg, respectively. Ewedu (*C. olitorius*) showed extremely high Pb (155.55 mg/kg) and Co (115.35 mg/kg) concentrations relative to the guideline values of 2.0 mg/kg Pb and 0.5 mg/kg Co presented in Table 1. Maize (*Z. mays*) also showed very high Cr concentration (110.05 mg/kg), far above the 1.6 mg/kg guideline value, which underscores the intensity of contamination at the site.

During the dry season, metal burdens generally increased further in several species, particularly for Cd, Zn and Pb. Cassava leaves (*M. esculenta*) and spinach (*S. oleracea*) exhibited extremely elevated Cd concentrations of 125.05 mg/kg and 127.65 mg/kg, respectively, while cassava leaves also recorded 34.00 mg/kg Zn. Maize (*Z. mays*) and cocoyam leaves (*X. sagittifolium*) showed markedly elevated Pb concentrations of 148.85 mg/kg and 55.15 mg/kg, respectively. Overall, the values in Table 1 indicate that, in both seasons, many plant–metal combinations exceeded recommended safe limits, consistent with previous reports of heavy metal contamination of edible vegetables in industrial and roadside environments.

Table 1: Concentrations of heavy metals in plants at the study site

PLANT	Mn	Cu	Zn	Ni	Cd	Fe	Pb	Cr	Co
Wet season (mg/ kg)									
A	3.55	2.10	2.40	2.40	1.52	8.30	1.50	110.05	3.50
B	2.55	4.30	5.65	4.85	5.05	6.00	3.80	4.85	3.35
C	4.10	4.85	3.95	50.10	5.90	2.90	2.45	51.60	11.05
D	1.65	7.80	2.65	4.10	4.20	111.50	3.60	1.55	3.75
E	4.85	8.20	6.30	3.30	6.00	7.05	155.55	5.00	115.35
F	2.65	4.50	2.90	56.55	4.70	4.95	4.45	60.70	4.70
Dry season (mg/ kg)									
A	5.40	11.75	2.20	2.05	35.75	3.25	148.85	3.70	4.20
B	8.85	4.35	34.00	9.00	125.05	55.20	10.55	4.30	10.05
C	5.45	5.95	7.10	4.30	9.95	4.90	55.15	13.15	4.40
D	5.20	2.75	10.55	4.90	127.65	10.45	5.50	4.55	1.80
WHO limit (mg/ kg)	400	10.0	0.6	10.0	0.02	150	2.0	1.6	0.5

KEY: A = Maize; **B** = Cassava; **C** = Cocoyam Leaf; **D** = Spinach; **E** = Ewedu; **F** = Scent Leaf

Metal uptake by plants

The results indicate that root-associated food crops, especially cassava and cocoyam leaves, showed substantial uptake of several heavy metals from the contaminated environment. However, some leafy vegetables also behaved as strong accumulators, particularly ewedu for Pb and Co, and spinach for Cd during the dry season. This pattern suggests that both plant type and metal-specific availability influenced uptake at the site.

Heavy metal bioavailability in plants is controlled by several interacting factors, including the abundance of the metal in soil, its chemical form, soil physicochemical properties and plant species characteristics. Previous studies have shown that leafy vegetables can act as effective accumulators of heavy metals, often storing them in above-ground tissues without obvious visible toxicity symptoms (Intawongse & Dean, 2006; Khan *et al.*, 2015). The present findings support those observations and further demonstrate that edible plants grown near battery recycling operations may become important pathways of dietary metal exposure.

The seasonal difference observed in this study may also reflect changes in soil moisture, metal solubility and plant physiological response. The absence of ewedu (*Corchorus olitorius*) and scent leaf (*Ocimum gratissimum*) in the dry season may indicate that these species were unable to tolerate the combined effects of drought and site contamination. In contrast, the surviving species continued to accumulate metals at levels that raise ecological and public health concerns.

Metal Accumulation Index (MAI)

Table 2 summarizes the quantity of heavy metals taken up by each of the plants and the value of MAI which indicates the ability of the plants to store toxic metals in the two seasons. Plants with high value of MAI may be used as a yardstick in understanding the difference between contaminated and non-contaminated environments. The MAI reflects the ability of plants to tolerate elevated metal burdens but also highlights the potential magnitude of harm to consumers of these crops. The higher the MAI, the greater the cumulative metal load in the edible tissue and the greater the potential health risk associated with consumption. The high MAI of the plant samples can be ascribed to the activities of the battery recyclers and other sister industries in the study site. Species with high MAI values can therefore be considered metal-tolerant and may serve as useful sinks or candidate phytoremediation species in polluted agricultural landscapes (Jamil *et al.*, 2009; Nadgorska- Socha *et al.*, 2016).

Plant E (*Corchorus olitorius*) and Plant F (*Ocimum gratissimum*) rely on adequate water supply during the wet season, which facilitated rapid uptake of heavy metals and may have contributed to their poor survival under prolonged contamination. Ingestion of vegetables produced under such conditions is likely to have adverse effects on the health of local residents. Conversely, water scarcity in the dry season restricts both plant growth and metal uptake in some species, although surviving crops still show high MAI values and remain important pathways of exposure.

Table 2: Metal accumulation index for wet and dry season

	Mn	Cu	Zn	Ni	Cd	Fe	Pb	Cr	Co	MAI
WET										
A	3.55 ± 0.03	2.10 ± 0.21	2.40 ± 0.21	2.40 ± 0.02	1.52 ± 0.02	8.30 ± 0.17	1.50 ± 0.02	110.05 ± 0.02	3.50 ± 0.25	547.97
B	2.55 ± 0.04	4.30 ± 0.05	5.65 ± 0.34	4.85 ± 0.02	5.05 ± 0.03	6.00 ± 0.15	3.80 ± 0.02	4.85 ± 0.17	3.35 ± 0.26	81.08
C	4.10 ± 0.11	4.85 ± 0.01	3.95 ± 0.21	50.10 ± 0.31	5.90 ± 0.10	2.90 ± 0.49	2.45 ± 0.00	51.60 ± 0.20	11.05 ± 0.04	113.99
D	1.65 ± 0.03	7.80 ± 0.51	2.65 ± 0.13	4.10 ± 0.01	4.20 ± 0.40	111.50 ± 0.30	3.60 ± 0.09	1.55 ± 0.24	3.75 ± 0.20	101.70
E	4.85 ± 0.21	8.20 ± 0.30	6.30 ± 0.42	3.30 ± 0.05	6.00 ± 0.20	7.05 ± 0.03	155.55 ± 0.51	5.00 ± 0.21	115.35 ± 2.31	76.22
F	2.65 ± 0.03	4.50 ± 0.00	2.90 ± 0.11	56.55 ± 0.22	4.70 ± 0.10	4.95 ± 0.06	4.45 ± 0.37	60.70 ± 0.20	4.70 ± 0.35	76.78
DRY										
A	4.20 ± 0.01	5.35 ± 0.22	5.40 ± 0.20	11.75 ± 0.02	2.20 ± 0.20	35.75 ± 0.51	3.25 ± 0.12	148.85 ± 0.55	3.70 ± 0.06	155.88
B	10.05 ± 0.06	4.50 ± 0.20	8.85 ± 0.06	4.35 ± 0.15	34.00 ± 0.00	125.05 ± 0.03	55.20 ± 0.26	10.55 ± 0.95	4.30 ± 0.26	479.19
C	4.40 ± 0.04	3.30 ± 0.16	5.45 ± 0.17	55.95 ± 0.04	7.10 ± 0.10	9.95 ± 0.21	4.90 ± 0.10	55.15 ± 0.09	13.15 ± 0.10	237.49
D	1.80 ± 0.02	5.20 ± 0.17	5.20 ± 0.20	2.75 ± 0.10	10.55 ± 0.04	127.65 ± 0.26	10.45 ± 0.05	5.50 ± 0.45	4.55 ± 0.02	141.83

Table 2 also summarizes the Metal Accumulation Index (MAI) of each of the plant species during the wet and dry seasons in terms of mean heavy metal concentrations and the corresponding standard deviations. Table represents the mean (first value) and standard deviation of Mn, Cu, Zn, Ni, Cd, Fe, Pb, Cr and Co, was obtained by equation 1, (Liu *et al.*, 2007). This approach weights metals that are both high in concentration and relatively stable (low variability), and has been widely used to characterize multi-metal accumulation in plants in urban and industrial environments.In the wet season, maize (*Zea mays*; A) has the highest MAI (547.97), driven largely by very high and precise Cr levels (110.05 ± 0.02 mg/kg) and substantial contributions from Ni and Cd, indicating strong cumulative metal pressure on this cereal crop near the recycling site. Root and leafy vegetables such as cassava leaves (*Manihot esculenta*; B), cocoyam leaves (*Xanthosoma sagittifolium*; C), spinach (*Spinacia oleracea*; D), ewedu (*Corchorus olitorius*; E) and scent leaf (*Ocimum gratissimum*; F) show MAI values between about 76 and 114, comparable to or higher than values reported for tree and herb species in other polluted cities (e.g. MAI = 2.56 for *Sophora japonica* in Yan'an, 9.0 in Beijing), confirming that the Ogijo plants are experiencing much more intense multi-metal contamination than typical urban bio monitors. During the dry season, MAI values increase further for most surviving plants, reflecting the combined effect of higher dry-season metal concentrations (especially Cd, Pb and Zn) and relatively low standard deviations. Cassava leaves (*M. esculenta*; B) reach an MAI of 479.19 and cocoyam leaves (*X. sagittifolium*; C) 237.49, which are far above the MAI values considered indicative of contaminated environments in earlier applications of the index and similar to or higher than those reported near heavy-industry zones and roadsides in other regions. Spinach (*S. oleracea*; D) also shows an elevated MAI (141.83), while maize (A) retains a high MAI (155.88), confirming that both cereal and vegetable crops act as strong accumulators during the dry season. This seasonal contrast is in line with the existing literature which indicates that MAI is also responsive to changes in metal loading and plant physiological condition with season and pollution open intervals. In line with Liu *et al.*, (2007) and similar work on MAI in Beijing and Yan'an, the high wet and dry-season MAI values in this table indicate that all studied species are growing under severe multi-metal stress, with dry season conditions amplifying overall accumulation and likely health risks for consumers. Note that MAI is dimensionless.

Table 3: Bioaccumulation factor (BAF) for Cd, Pb, Zn and Co in plants during wet and dry seasons at the battery recycling site

Plant Species		Season	C_{soil} Cd (mg/kg)	C_{plant} Cd (mg/kg)	BAF Cd	C_{soil} Pb (mg/kg)	C_{plant} Pb (mg/kg)	BAF Pb	C_{soil} Zn (mg/kg)	C_{plant} Zn (mg/kg)	BAF Zn	C_{soil} Co (mg/kg)	C_{plant} Co (mg/kg)	BAF Co
A	Maize	Wet	16.687	1.52	0.09	13.861	1.50	0.11	13.078	2.40	0.18	6.728	3.50	0.52
B	Cassava leaf	Wet	16.687	5.05	0.30	13.861	3.80	0.27	13.078	5.65	0.43	6.728	3.35	0.50
C	Cocoyam leaf	Wet	16.687	5.90	0.35	13.861	2.45	0.18	13.078	3.95	0.30	6.728	11.05	1.64
D	Spinach	Wet	16.687	4.20	0.25	13.861	3.60	0.26	13.078	2.65	0.20	6.728	3.75	0.56
E	Ewedu	Wet	16.687	6.00	0.36	13.861	155.55	11.22	13.078	6.30	0.48	6.728	115.35	17.14
F	Scent leaf	Wet	16.687	4.70	0.28	13.861	4.45	0.32	13.078	2.90	0.22	6.728	4.70	0.70
A	Maize	Dry	6.238	35.75	5.73	8.887	3.70	0.42	8.742	2.20	0.25	10.056	5.35	0.53
B	Cassava leaf	Dry	6.238	125.05	20.06	8.887	10.55	1.19	8.742	34.00	3.89	10.056	4.50	0.45
C	Cocoyam leaf	Dry	6.238	9.95	1.60	8.887	55.15	6.21	8.742	7.10	0.81	10.056	3.30	0.33
D	Spinach	Dry	6.238	127.65	20.46	8.887	5.50	0.62	8.742	10.55	1.21	10.056	5.20	0.52

Bioaccumulation factor (BAF)

The bioaccumulation factor (BAF) values presented in Table 3 show clear metal-specific and seasonal patterns of soil-to-plant transfer. In the wet season, BAF values for Cd and Zn were below 1.0 in all species, indicating limited enrichment relative to soil concentrations. For Co, most species also had BAF values below 1.0, but cocoyam leaves and ewedu recorded values above 1.0, indicating enhanced uptake. Ewedu behaved as a particularly strong accumulator for Pb and Co, with BAF values of approximately 11.22 and 17.14, respectively, while cocoyam leaves showed Co BAF of 1.64.

In the dry season, BAF values increased substantially for several metals. Cassava leaves and spinach showed very high Cd accumulation, with BAF values of approximately 20.06 and 20.46, respectively, while maize also showed elevated Cd accumulation with a BAF of 5.73. Cocoyam leaves recorded a very high Pb BAF of 6.21, and cassava leaves showed notable Zn accumulation with a BAF of 3.89. Spinach also exceeded unity for Zn in the dry season, with a BAF of 1.21.

These findings confirm that dry-season conditions favored the transfer of several toxic metals from soil to edible plant tissues. Lower soil moisture, increased dust deposition and changes in metal mobility may have contributed to the stronger dry-season uptake pattern observed in cassava, cocoyam, spinach and maize. The results therefore indicate that dry-season cultivation around the battery recycling site poses a particularly high risk of metal accumulation in food crops.

Table 4: Estimated Daily Intake and Health Risk Index (HRI) for Cadmium, Lead, Zinc and Cobalt in Edible Plant Species during Wet and Dry Seasons Compared with USEPA/WHO Reference Doses

Plant (species)	Season	Metal	Cplant (mg/kg)	EDI = (Cplant×0.2)/70 (mg/kg/day)	RfD (mg/kg/day)	HRI = EDI/RfD
Cassava leaf (*Manihot esculenta*)	Wet	Cd	5.05	0.01443	0.0010	14.43
Cassava leaf (*M. esculenta*)	Dry	Cd	125.05	0.35729	0.0010	357.29
Maize (*Zea mays*)	Wet	Cd	1.52	0.00434	0.0010	4.34
Spinach (*Spinacia oleracea*)	Dry	Cd	127.65	0.36471	0.0010	364.71
Ewedu (*Corchorus olitorius*)	Wet	Cd	6.00	0.01714	0.0010	17.14
Cassava leaf (*M. esculenta*)	Wet	Pb	3.80	0.01086	0.0035	3.10
Cassava leaf (*M. esculenta*)	Dry	Pb	10.55	0.03014	0.0035	8.61
Ewedu (*C. olitorius*)	Wet	Pb	155.55	0.44443	0.0035	127.01
Cocoyam leaf (*X. sagittifolium*)	Dry	Pb	55.15	0.15757	0.0035	45.02
Maize (*Z. mays*)	Dry	Pb	3.70	0.01057	0.0035	3.02
Cassava leaf (*M. esculenta*)	Wet	Zn	5.65	0.01614	0.3000	0.05
Cassava leaf (*M. esculenta*)	Dry	Zn	34.00	0.09714	0.3000	0.32
Spinach (*S. oleracea*)	Dry	Zn	10.55	0.03014	0.3000	0.10
Ewedu (*C. olitorius*)	Wet	Zn	6.30	0.01800	0.3000	0.06
Cassava leaf (*M. esculenta*)	Wet	Co	3.35	0.00957	0.0300	0.32
Ewedu (*C. olitorius*)	Wet	Co	115.35	0.32957	0.0300	10.99
Cocoyam leaf (*X. sagittifolium*)	Wet	Co	11.05	0.03157	0.0300	1.05
Spinach (*S. oleracea*)	Dry	Co	5.20	0.01486	0.0300	0.50
Maize (*Z. mays*)	Wet	Co	3.50	0.01000	0.0300	0.33

Health Risk Index (HRI)

Table 4 presents the estimated daily intake (EDI) and Health Risk Index (HRI) values for Cd, Pb, Zn and Co based on an assumed vegetable consumption rate of 0.2 kg/day and an average body weight of 70 kg. The results show that non-carcinogenic health risks associated with Cd, Pb and Co are unacceptable for several plant–season combinations when compared with the corresponding USEPA/WHO oral reference doses.

For Cd, all evaluated plant samples produced HRI values above 1.0, even in the wet season. Wet-season cassava leaves, maize and ewedu recorded Cd HRI values of 14.43, 4.34 and 17.14, respectively, while dry-season cassava leaves and spinach reached extremely high HRI values of 357.29 and 364.71, respectively. These results indicate that Cd exposure through the consumption of vegetables grown at the site could pose a serious health risk to local residents.

Lead also showed substantial dietary risk in several species. Wet-season cassava leaves and ewedu had Pb HRI values of 3.10 and 127.01, respectively, while dry-season cassava leaves, cocoyam leaves and maize recorded HRI values of 8.61, 45.02 and 3.02, respectively. These values are far above the hazard threshold of 1.0 and indicate unsafe dietary exposure.

In contrast, Zn remained below the hazard threshold in all evaluated cases, despite elevated plant concentrations in some species. This is likely because Zn is an essential nutrient with a comparatively higher oral reference dose. Cobalt showed mixed behavior: most species had Co HRI values below 1.0, but wet-season ewedu and cocoyam leaves exceeded the threshold, with values of 10.99 and 1.05, respectively. Overall, the HRI results demonstrate that consumption of vegetables grown near the battery recycling site may expose local populations to serious non-carcinogenic risks, especially from Cd and Pb.

CONCLUSION

This study demonstrates that edible plants cultivated around the battery recycling facility in Ogijo are significantly contaminated with toxic metals and pose substantial food-safety concerns for nearby residents. Concentrations of Zn, Cd, Pb, Cr and Co in several plant species exceeded recommended guideline values in both wet and dry seasons, with the dry season generally showing more severe contamination. The combined evidence from BAF, MAI and HRI indicate that the site is not suitable for safe cultivation of food crops, particularly leafy vegetables that readily accumulate metals in edible tissues. The very high HRI values recorded for Cd and Pb in cassava leaves, spinach and ewedu indicate unacceptable non-carcinogenic risks to consumers. Overall, the findings confirm that battery recycling activities have created a contaminated agricultural environment that requires urgent regulatory and remedial attention.

RECOMMENDATIONS

i. Food-crop cultivation should be discouraged within and around the immediate vicinity of the battery recycling facility until the site is properly assessed and remediated.

ii. Relevant environmental and public-health agencies should conduct routine monitoring of soils, irrigation water and edible plant tissues in the area to track contamination trends and protect surrounding communities.

iii. The battery recycling operation should be subjected to stricter environmental control measures, including improved waste handling, emission control and containment of contaminated residues.

iv. Remediation strategies such as removal of contaminated topsoil, stabilization of polluted zones and targeted phytoremediation should be considered to reduce metal mobility and human exposure.

v. Community sensitization programmes should be implemented to inform residents and farmers about the health risks associated with consuming vegetables grown near the recycling site**.**

vi. Further studies should examine additional exposure pathways, including groundwater, airborne dust and long-term dietary intake, to provide a more comprehensive risk assessment for the affected population.

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