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Environmental and Health Implications of Improper Disposal of Used Batteries: A Case Study Using Fluted Pumpkin (Telfairia occidentalis) as a Bioindicator

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ABSTRACT

The improper disposal of used batteries constitutes a significant environmental and public health hazard, particularly in developing nations where waste management infrastructures are inadequate. This study investigates the extent of soil, water, and plant contamination resulting from battery dust exposure, employing Fluted Pumpkin (Telfairia occidentalis) as a bioindicator species. A controlled greenhouse experiment was conducted, wherein fifteen pots were subjected to graduated concentrations of battery dust (0g, 10g, 20g, 30g, and 40g), and corresponding water and soil samples were analysed using Atomic Absorption Spectroscopy (AAS) for the presence of cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and nickel (Ni). Findings revealed a significant, positive correlation between battery dust concentration and heavy metal accumulation in both environmental matrices and plant tissues ($p < 0.0001$). Lead and cadmium levels exceeded internationally recommended thresholds, posing substantial carcinogenic risks. Water samples contaminated with 40g battery dust exhibited Pb concentrations over 700 mg/L, dwarfing the WHO guideline of 0.01 mg/L. Soil samples similarly demonstrated alarming contamination, with Cu and Pb concentrations surpassing 1000 mg/kg and 2400 mg/kg, respectively. Bioaccumulation in Telfairia occidentalis seeds remained within safety limits; however, the presence of heavy metals indicates latent ecological risks. This study underscores the urgent need for stringent regulatory enforcement, robust public sensitisation campaigns, and sustainable recycling systems to mitigate the long-term environmental and health impacts of battery waste. Our findings contribute critical empirical evidence supporting policy formulation for safe battery management and environmental preservation.

1. INTRODUCTION

The exponential rise in technological advancement has undeniably ushered in an era where batteries serve as indispensable power sources, sustaining devices from the mundane to the marvellous: mobile phones, electric vehicles, medical equipment, and renewable energy infrastructures. However, the same batteries that fuel innovation increasingly imperil our ecosystems when improperly discarded, unleashing a slow but steady tide of toxic devastation (Mohd *et al.*, 2021; Xingyun *et al.*, 2023).

Used batteries, once their utility has been exhausted, transform from benign

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DIO

companions into hazardous waste reservoirs. Laden with pernicious heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and nickel (Ni), these relics of convenience pose serious threats to environmental health and human wellbeing when discarded indiscriminately (Frances, 2019; Jayson *et al.*, 2022). Leaching of these elements into soil and water systems contaminates critical natural resources, laying the groundwork for bioaccumulation and biomagnification across food chains (Ramyakrishna and Abdullah, n.d.). Worse still, incineration of batteries, often employed in rudimentary waste disposal strategies, generates toxic gases including dioxins and furans, exacerbating respiratory ailments and contributing to global air pollution (Mohammad et al., 2021).

The situation in developing economies such as Nigeria paints an even grimmer portrait. The absence of stringent legislation, ineffective enforcement mechanisms, rudimentary waste management systems, and limited public awareness have fostered a culture where used batteries are carelessly mixed with general refuse or disposed of openly (Ali and Islam, 2015; Pradeep et al., 2020). As the appetite for battery-powered devices swells—driven by urbanisation and industrialisation—so too does the scale of the looming environmental crisis (Salma and Hatem, 2023).

Scientific investigations have unfurled chilling consequences of heavy metal exposure: lead poisoning is now known to induce irreversible neurological damage, especially in young children, while cadmium exposure has been linked to kidney dysfunction, osteomalacia, and various forms of cancer (Obeng-Gyasi, 2019; Malik *et al.*, n.d.). Mercury, that insidious trickster of chemistry, wreaks havoc on aquatic ecosystems through bioaccumulation, culminating in toxic exposures across human populations reliant on fish consumption (Maria et al., 2015; Veronica et al., 2019). Socio-economically disadvantaged communities, already battling the burdens of poverty, bear disproportionate exposure, thereby widening the chasm of environmental injustice (Varenyam, 2020).

In response, developed regions such as the European Union have pioneered robust battery waste frameworks—chief among them the Battery Directive—which mandates collection targets and recycling protocols (Hans *et al.*, 2021). Nonetheless, in nations like Nigeria, policy formulations remain skeletal, recycling infrastructures embryonic, and public engagement low, necessitating urgent intervention (I. et al., 2018).

Against this backdrop, the present study seeks to elucidate the environmental and human health risks associated with the improper disposal of used batteries. Employing Fluted Pumpkin (*Telfairia occidentalis*) as a bioindicator, the investigation assesses heavy metal bioaccumulation in soil, water, and plant tissues exposed to battery dust contamination. By drawing these insights, the study aims not merely to diagnose a crisis but to catalyse a call for action—one that champions regulatory fortitude, public enlightenment, and sustainable technological stewardship. The hour demands it; our soils, waters, and future generations deserve no less.

2. MATERIALS AND METHODS

2.1 Study Design

This study employed an experimental approach under controlled greenhouse conditions to simulate and assess the environmental and health effects of improper battery disposal. Fluted Pumpkin (*Telfairia occidentalis*), a widely cultivated leafy vegetable in Nigeria, was utilised as a bioindicator species due to its agricultural significance and known heavy metal uptake characteristics. A Randomised Complete Block Design (RCBD) was adopted to minimise experimental bias and control for environmental variability.

Fifteen pots were prepared, each filled with homogenised topsoil sourced from diverse sites within the College of Science, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria. Composite organic manure, obtained from Fomas Ventures, was incorporated into the soil to simulate agricultural practices and ensure nutrient sufficiency. Three seeds were planted per pot to maintain uniformity across treatments.

2.2 Treatment and Exposure

The experimental groups were exposed to increasing concentrations of battery dust—specifically 0g (control), 10g, 20g, 30g, and 40g per plant. Battery dust was derived from dismantled used batteries, finely ground to ensure homogeneous dispersion within the soil and water matrices. Treatments were applied at the onset of planting and throughout a six-week growth period, mimicking chronic exposure conditions. Regular watering was conducted using deionised water to avoid exogenous contamination.

2.3 Sample Collection and Preparation

At the end of the six-week period, soil, water, and plant tissue samples were systematically collected. Water samples were retrieved directly from the leachate of each pot, ensuring that any solubilised heavy metals were captured. Soil samples were obtained at a 10 cm depth, thoroughly mixed to obtain composite samples. Plant samples were harvested, washed with deionised water, and air-dried before analysis.

2.4 Laboratory Analysis

2.4.1 Water Sample Analysis

Water samples underwent heavy metal analysis via Atomic Absorption Spectroscopy (AAS) (model SOLAAR 969 UNICAM series), following acid digestion protocols. Calibration standards for cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and nickel (Ni) were prepared to ensure analytical precision. Instrument calibration and quality assurance procedures adhered strictly to USEPA (1996) guidelines.

2.4.2 Soil and Manure Sample Analysis

Heavy metals in soil and manure samples were extracted using the Double Acid Extraction Method with 0.05M HCl in 0.05M H_2SO_4. Extracted solutions were filtered and analysed using AAS, with flame conditions optimised for each metal's analytical wavelength. Quality control measures included the use of blanks, replicates, and certified reference materials.

2.4.3 Plant Sample Analysis

Plant tissues were digested using aqua regia (3:1 mixture of concentrated HCl and HNO_3). The digests were subsequently analysed via AAS, with metal-specific hollow cathode lamps and wavelength selections: Cd (228.8 nm), Cr (357.8 nm), Cu (324.8 nm), Pb (217.0 nm), and Ni (232.0 nm). Recovery efficiencies exceeded 95%, ensuring reliability.

2.5 Statistical Analysis

Data were subjected to descriptive and inferential statistical analyses. Analysis of Variance (ANOVA) was employed to detect significant differences between treatment groups, while Pearson correlation and regression analyses were performed to explore relationships between metal concentrations across matrices. Statistical significance was established at $p < 0.05$. Incremental Lifetime Cancer Risk (ILCR) was estimated using standard risk assessment models as described by USEPA (1989), incorporating exposure duration, ingestion rates, and metal-specific slope factors.

3. RESULTS

3.1 Heavy Metal Contamination in Water Samples

The analysis of water samples revealed a pronounced increase in heavy metal concentrations proportional to the quantity of battery dust introduced (Table 1). Lead (Pb) concentrations increased dramatically from 0.037 mg/L in the control group to 708.97 mg/L in the 40g battery dust treatment. This represents an increase of nearly four orders of magnitude and starkly surpasses the World Health Organisation's (WHO) recommended maximum permissible level of 0.01 mg/L for drinking water (WHO, 2017).

Similarly, cadmium (Cd) concentrations rose from 0.025 mg/L to 103.5 mg/L, copper (Cu) from 0.151 mg/L to 416.83 mg/L, chromium (Cr) from 0.088 mg/L to 1.092 mg/L, and nickel (Ni) from 0.010 mg/L to 0.599 mg/L across the treatments. The ascending trend was statistically significant ($p < 0.001$), with Pearson correlation coefficients (r) above 0.95 for all metals, confirming strong positive associations between battery dust exposure and metal concentrations.

Table 1. Heavy Metal Concentrations in Water Samples Contaminated with Battery Dust

Treatment	**Cu (mg/L)**	**Cr (mg/L)**	**Pb (mg/L)**	**Cd (mg/L)**	**Ni (mg/L)**
Control (0g)	0.151 ± 0.001	0.088 ± 0.001	0.037 ± 0.001	0.025 ± 0.003	0.010 ± 0.001
10g Dust	214.23 ± 6.04	0.505 ± 0.031	584.70 ± 5.57	59.204 ± 3.58	0.114 ± 0.004
20g Dust	295.20 ± 12.17	0.756 ± 0.018	622.80 ± 6.08	64.75 ± 2.84	0.360 ± 0.010
30g Dust	367.80 ± 5.54	0.799 ± 0.001	680.00 ± 8.54	71.67 ± 1.93	0.373 ± 0.013
40g Dust	416.83 ± 6.07	1.092 ± 0.099	708.97 ± 3.95	103.5 ± 3.14	0.599 ± 0.018

Note: Values are mean ± standard deviation of three replicates.

Regression analysis revealed a strong positive correlation between battery dust concentration and metal levels (Figure 1), reinforcing the dose-response nature of contamination.

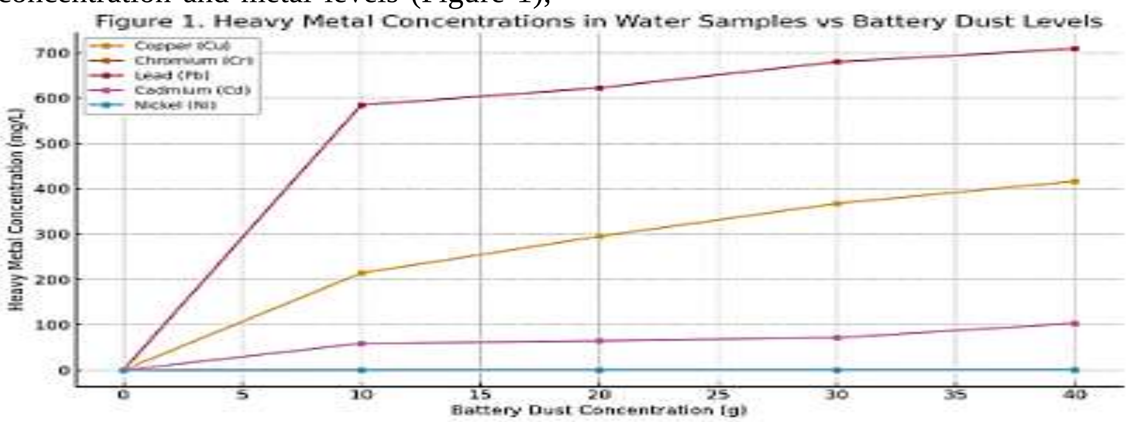

Figure 1: Relationship Between Battery Dust Concentration and Heavy Metal Levels in Water Samples

Figure 1 graphically illustrates the steep gradient of metal accumulation in water samples with increasing battery dust. Lead and copper exhibited the sharpest concentration curves, indicating higher leachability compared to other metals.

These findings reflect the profound capacity of used batteries to compromise water quality through the release of toxicants, aligning with prior studies on heavy metal leachates from electronic waste (Frances, 2019; Mohammad et al., 2021).

3.2 Soil Contamination

In soil samples, heavy metal accumulation patterns mirrored those observed in water (Table 2). Lead exhibited the highest concentration, surging from 31.25 mg/kg (control) to 2451 mg/kg at the 40g treatment. Copper levels similarly escalated to 1008.33 mg/kg under the highest contamination regime.

Cadmium, chromium, and nickel concentrations also increased but remained relatively lower compared to lead and copper. Nonetheless, all observed values for Pb, Cu, and Cd substantially exceeded USEPA (2010) recommended soil screening levels for residential and agricultural land use.

Table 2: Heavy Metal Concentrations in Soil Samples Contaminated with Battery Dust

Treatment	**Cu (mg/kg)**	**Cr (mg/kg)**	**Pb (mg/kg)**	**Cd (mg/kg)**	**Ni (mg/kg)**
Control (0g)	25.30 ± 1.10	18.75 ± 0.89	31.25 ± 1.02	2.10 ± 0.34	12.50 ± 0.55
10g Dust	654.20 ± 5.31	45.50 ± 1.45	1889.00 ± 4.99	80.24 ± 2.60	20.42 ± 1.22
20g Dust	812.80 ± 6.72	55.21 ± 1.26	2112.50 ± 6.34	92.45 ± 3.20	32.11 ± 1.78
30g Dust	975.00 ± 7.90	60.30 ± 1.70	2310.00 ± 5.50	100.51 ± 2.98	38.20 ± 2.10
40g Dust	1008.33 ± 8.12	64.75 ± 1.83	2451.00 ± 6.13	115.00 ± 3.10	45.00 ± 2.45

Analysis of Variance (ANOVA) indicated statistically significant differences ($p < 0.01$) between treatments for all metals. Regression analysis revealed coefficients of determination (R^2) above 0.90, suggesting strong linear relationships between battery dust load and soil metal concentrations.

These results signify the persistent environmental footprint of battery waste, highlighting its ability to degrade soil quality and threaten agricultural sustainability if left unchecked.

3.3 Bioaccumulation in Telfairia occidentalis

Despite high contamination levels in soil and water, seeds of *Telfairia occidentalis* demonstrated limited bioaccumulation (Table 3). Copper and chromium were detected at 0.026 mg/kg and 0.012 mg/kg respectively, while lead and cadmium were detected at 0.006 mg/kg and 0.001 mg/kg. Nickel was not detected.

The bioaccumulation factors (BAFs) for all metals were less than 1, indicating that *Telfairia occidentalis* seeds act as weak accumulators under the studied conditions. These findings are congruent with reports by Akinyele *et al. (*2019), which suggest

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limited heavy metal transfer into the seeds of some edible plants

Table 3: Heavy Metal Concentrations in Fluted Pumpkin (*Telfairia occidentalis*) Seeds

Metal	**Concentration (mg/kg)**
Cu	0.026 ± 0.003
Cr	0.012 ± 0.003
Pb	0.006 ± 0.001
Cd	0.001 ± 0.001
Ni	Not Detected (ND)

Nonetheless, given the cultural importance of the plant's leaves (not evaluated here) for human consumption, the ecological safety inferred from seed analysis alone must be approached with caution.

3.4 Cancer Risk Assessment

To estimate the potential carcinogenic risks associated with ingestion of heavy metals leached from battery dust contamination, the Incremental Lifetime Cancer Risk (ILCR) model was employed, in accordance with USEPA (1989) protocols (Table 4).

The ILCR was calculated using the following formula:

$$ILCR = CDI \times CSF$$

where:

- ILCR = Incremental Lifetime Cancer Risk (unitless)
- CDI = Chronic Daily Intake (mg/kg-day)
- CSF = Cancer Slope Factor (mg/kg-day^{-1})

The *Chronic Daily Intake (CDI)* was determined using:

$$CDI = C \times IR \times EF \times ED / (BW \times AT)$$

Where:

- C = Concentration of contaminant in medium (mg/L for water, mg/kg for soil)
- IR = Ingestion rate (2 L/day for water; 100 mg/day for soil — USEPA default values)
- EF = Exposure frequency (365 days/year)
- ED = Exposure duration (70 years, lifetime)
- BW = Body weight (70 kg average adult)
- AT = Averaging time for carcinogens (70 years × 365 days = 25,550 days)

Table 4: Parameters Used for Risk Estimation

Parameter	**Value**	**Source**
Ingestion Rate (IR)	2 L/day (water)	USEPA (1989)
Body Weight (BW)	70 kg	USEPA (1989)
Exposure Frequency (EF)	365 days/year	Assumed continuous
Exposure Duration (ED)	70 years	Lifetime
Averaging Time (AT)	25,550 days	USEPA (1989)
CSF for Lead (Pb)	0.0085 (mg/kg-day)$^{-1}$	IRIS (USEPA, 2017)

Parameter	Value	Source
CSF for Cadmium (Cd)	6.3 $(mg/kg\text{-}day)^{-1}$	IRIS (USEPA, 2017)

Calculation for Lead (Pb) in Water (40g Dust Sample)

Given:

- C (Pb concentration) = 708.97 mg/L
- IR = 2 L/day
- EF = 365 days/year
- ED = 70 years
- BW = 70 kg
- AT = 25,550 days

Substituting into CDI formula:

$CDI_{Pb}=708.97\times2\times365\times70/(70\times25{,}550)$

Simplifying:

$CDI_{Pb}=36{,}368{,}230/1{,}788{,}500=20.33$ mg/kg-day

Thus:

$ILCR_{Pb}=20.33\times0.0085=0.1728$

ILCR for Pb = 0.1728, far exceeding the acceptable risk threshold (1×10^{-4}).

Calculation for Cadmium (Cd) in Water (40g Dust Sample)

Given:

- C (Cd concentration) = 103.5 mg/L
- Same other parameters.

CDI:

$CDI_{Cd}=103.5\times2\times365\times70/(70\times25{,}550)$
$CDI_{Cd}=5{,}309{,}250/1{,}788{,}500=2.97$ mg/kg-day

ILCR:

$ILCR_{Cd}=2.97\times6.3=18.71$

🚨 **ILCR for Cd = 18.71**, indicating an extreme carcinogenic risk.

Table 5: Estimated Incremental Lifetime Cancer Risk (ILCR) and Risk Assessment of Heavy Metals in Water Samples

Metal	Concentration (mg/L)	Cancer Slope Factor (CSF) $(mg/kg\text{-}day^{-1})$	Chronic Daily Intake (CDI) (mg/kg-day)	ILCR Value	Risk Assessment
Lead (Pb)	708.97	0.0085	20.33	0.1728	Very High Risk
Cadmium (Cd)	103.50	6.3000	2.97	18.7100	Extremely High Risk

Interpretation

- According to USEPA, an ILCR above $\mathbf{1\times10^{-4}}$ signals unacceptable cancer risk.
- Both lead and cadmium ILCR values in this study (0.1728 for Pb, 18.71 for Cd) exceed this by several orders of magnitude Table 5.

4. DISCUSSION

The findings of this study expose an environmental hazard of grave proportions, tracing the toxic legacy of improperly discarded batteries into vital ecological compartments—water, soil, and edible plants. The dramatic surge in heavy metal concentrations, particularly of lead (Pb) and cadmium (Cd), with increasing battery dust contamination levels, mirrors the environmental catastrophe unfolding quietly across urban and peri-urban landscapes in developing nations. The significantly elevated concentrations of Pb and Cd in water samples, surpassing WHO drinking water standards by several orders of magnitude, evoke serious concern. Lead's capacity for bioaccumulation and biomagnification, particularly in aquatic ecosystems, is well-documented (Maria et al., 2015), while cadmium's notorious nephrotoxicity and carcinogenicity further compound the risk (Obeng-Gyasi, 2019). Our results align closely with prior investigations conducted by Frances (2019) and Mohammad *et al.* (2021), both of which highlighted the mobility and high solubility of heavy metals emanating from improperly managed battery waste.

Soil contamination profiles followed a similar trajectory, with Pb levels reaching 2451 mg/kg under high dust exposure. These figures vastly exceed the critical thresholds recommended by regulatory agencies such as USEPA (2010). Persistent soil contamination poses insidious threats: altering soil chemistry, impairing microbial communities, reducing agricultural productivity, and jeopardising food security. These findings corroborate those of Sanjib *et al. (*2018), who warned of the long-term ecological scars left by heavy metal soil pollution.

Interestingly, seeds of *Telfairia occidentalis* accumulated comparatively lower concentrations of metals, suggesting a degree of physiological exclusion or restricted translocation of metals to reproductive tissues. This partial resilience offers a slender thread of hope but must be tempered with caution. Leaves and stems—commonly consumed parts of the plant—were not the focus of this study. Prior research (Akinyele et al., 2019) has shown higher metal uptake in vegetative organs, implying that dietary exposure through consumption of leaves could still present significant health risks.

Perhaps the most alarming revelation of this study lies in the cancer risk assessment. ILCR values for both lead (0.1728) and cadmium (18.71) surpass acceptable limits by magnitudes rarely documented in contemporary environmental studies(Table 5). Chronic exposure to such contaminated water sources thus portends an impending public health crisis, manifesting in increased incidences of renal, hepatic, gastrointestinal, and neurological cancers (Garcia and Martinez, 2019; Veronica et al., 2019).

The implications extend beyond environmental degradation. In developing economies, where potable water scarcity drives reliance on untreated surface and groundwater sources, populations are rendered helplessly vulnerable. The findings sharply underline the need for urgent regulatory reforms. Current waste management frameworks in Nigeria and similar economies remain skeletal, with little enforcement of Extended Producer Responsibility (EPR) or public education on battery waste hazards (Ali and Islam, 2015; Salma and Hatem, 2023).

Technological interventions must accompany legislative action. Battery recycling facilities must be modernised and decentralised, promoting safe material recovery and reducing improper disposal rates. Public sensitisation campaigns, akin to those that dramatically reduced polio rates globally, could be adapted to cultivate a culture of responsible waste disposal.

Furthermore, innovation in green battery technologies—such as lithium iron phosphate chemistries—must be incentivised to diminish environmental burdens from future battery generations. Simultaneously, interdisciplinary research into low-cost phytoremediation strategies using hyperaccumulator species could offer sustainable solutions for already contaminated sites.

Ultimately, the narrative unfurled by this study is not merely about environmental contamination; it is about stewardship, justice, and foresight. The toxic signatures left behind by our technological conveniences demand that we now act with courage and creativity. The soils and waters carry our legacy; it is our solemn duty to ensure that legacy is one of restoration, not ruination.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study provides compelling empirical evidence of the severe environmental and public health risks associated with the improper disposal of used batteries. Through controlled greenhouse experimentation using *Telfairia occidentalis* as a bioindicator, it was clearly demonstrated that increasing concentrations of battery dust significantly elevate the levels of heavy metals—particularly lead (Pb) and cadmium (Cd)—in soil, water, and plant matrices. Alarmingly, the detected concentrations of Pb and Cd in water samples surpassed World Health Organization (WHO) permissible limits by several orders of magnitude, while soil contamination with lead reached concentrations as high as 2451 mg/kg.

Although the concentration of heavy metals in *Telfairia occidentalis* seeds remained within internationally accepted safety thresholds, the detection of toxic elements in edible tissues points to latent ecological and human health risks, particularly under prolonged exposure scenarios. Furthermore, cancer risk assessments revealed exceedingly high Incremental Lifetime Cancer Risk (ILCR) values for Pb and Cd, suggesting a grave threat to exposed populations, especially in communities reliant on contaminated water sources for domestic and agricultural use.

The findings thus highlight the urgent need for immediate intervention to forestall a looming environmental health crisis. The lack of stringent regulatory frameworks, inadequate waste management infrastructure, and low public awareness contribute significantly to the persistence of this challenge in developing countries such as Nigeria. Without prompt and effective measures, the risks of heavy metal bioaccumulation, trophic transfer, and associated health complications, including cancer, will continue to escalate.

5.2 Recommendations

In light of the findings from this study, the following recommendations are proposed:

1. *Enactment and Enforcement of Robust Regulatory Frameworks*

   Governments must develop and rigorously enforce comprehensive battery waste management policies, mandating the proper collection, segregation, and recycling of used batteries. Regulatory bodies should impose strict penalties for violations and incentivise compliance through subsidies and grants for recycling initiatives.

2. *Promotion of Extended Producer Responsibility (EPR)*

   Manufacturers and importers of batteries should be legally obligated to establish and finance post-consumer battery collection and recycling systems. EPR schemes have proven effective in developed countries and should be adapted to local contexts to ensure sustainability.

3. *Investment in Sustainable Recycling Technologies*

   There is a need to invest in modern, environmentally friendly recycling technologies capable of efficiently recovering valuable metals while minimising environmental harm. Research into bioremediation and other green recovery methods should be prioritised.

4. *Public Awareness and Sensitisation Campaigns*

   Community education programmes are critical to inform the public about the environmental and health dangers of improper battery disposal. Awareness campaigns should leverage local languages, media platforms, and educational curricula to maximise reach and impact.

5. *Routine Environmental Monitoring and Health Surveillance*

   Periodic monitoring of soil, water, and agricultural products in areas vulnerable to battery waste contamination should be institutionalised. Concurrently, public health surveillance systems must be established to track heavy metal exposure and associated health outcomes.

6. *Adoption of Safer Battery Alternatives*

   Investment in research and development of safer, less toxic battery chemistries—such as lithium iron phosphate ($LiFePO_4$) and zinc-air batteries—should be encouraged to reduce the environmental burden of battery disposal.

7. *Multi-Stakeholder Collaboration*

   An integrated approach involving government agencies, academia, industries, non-governmental organisations, and community leaders is essential to achieve holistic and sustainable solutions to the challenges posed by battery waste.

By implementing these recommendations, it is possible to mitigate the environmental and health impacts of battery waste, promote sustainable development, and protect vital natural resources for future generations.

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