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Heavy metal contamination in soil surrounding a waste battery recycling facility

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ABSTRACT

In Mongolia, approximately 6,250 tons or 1.6 million lead-acid batteries are discarded annually. Of these, only 19% are recycled under poor conditions and exported, while the remaining 80% are improperly disposed into the environment, contributing significantly to soil, air, and water pollution. This study was conducted to determine the levels, vertical distribution, and chemical fractions of heavy metals in soils around a battery recycling plant in Nalaikh District, Ulaanbaatar, and to assess their environmental risks. A total of 78 soil samples were collected and analyzed for eight heavy metals (Cr, Cu, Pb, Ni, Zn, Co, As, Cd) using standard methods. The mobility of metals was assessed using sequential extraction. The results revealed that, except for Pb and As, most metals were within the permissible limits of MNS 5850:2019, though slightly elevated compared to control samples. The Pb concentration in the surface soil (0–5 cm) exceeded the standard by 52.6 times and the hazardous level by 687 mg/kg. Furthermore, 79.7% of Pb was in a mobile form, indicating high potential for environmental contamination. The enrichment factor (EF) of Pb was 18.5, and the geoaccumulation index (Igeo) ranged between 0.77 and 3.45, indicating moderate to heavy pollution. These findings confirm that contamination originates mainly from human activities, particularly from poor battery recycling practices. This study provides a detailed assessment of total and mobile heavy metal fractions, highlighting the urgent need to implement appropriate remediation technologies and protective measures such as fume capture systems.

KEYWORDS

Heavy metals, Contamination, Battery recycling, Geoaccumulation, Ulaanbaatar

1. INTRODUCTION

The production and recycling of lead-acid batteries are widely practiced around the world under both regulated and unregulated conditions [1]. In particular, the recycling of used batteries is one of the main sources of environmental pollution and poses serious risks to human health in many countries [2]. This is primarily because these operations often lack the necessary equipment and advanced technologies to control lead emissions, and in developing countries, this sector is poorly regulated [3]. Although used lead-acid battery recycling facilities may contribute to a country's economy to some extent, they can cause significant environmental harm if appropriate management and protective measures are not in place[4].

Over 20 million hectares of land worldwide are contaminated with heavy metals, including zinc (Zn), lead (Pb), nickel (Ni), arsenic (As), mercury (Hg), copper (Cu), cadmium (Cd), and chromium (Cr) [5]. The term "heavy metals" generally refers to metallic and metalloid elements with a density greater than 4±1 g/cm³ [6]. The most common heavy metals include Cr, As, Ni, Cd, Pb, Hg, Zn, and Cu. These metals can be present in various environmental media such as soil, water, air, and food. Through food chains, they can ultimately affect human health [7]. According to the Agency for Toxic Substances and Disease Registry (ATSDR), Hg, Pb, Cd, and As are among the most toxic heavy metals for both plants and humans [8]. A study conducted by the United States Environmental Protection Agency [9] considered dust particles smaller than 150 μm in size as hazardous when assessing health risks related to contaminated soil. In Japan, research showed that 90% of dust particles attached to children's hands were finer than 100 μm [10]. Heavy metal contamination in soils near industrial areas tends to increase, primarily due to waste emissions from small and medium-sized enterprises [11].

In particular, sources of Pb contamination include mining, metal processing, gasoline, electronic waste, paint, and battery manufacturing [12]. Arsenic (As) contamination is mainly linked to the use of agricultural pesticides, herbicides, and fertilizers [13]. Chromium (Cr) contamination typically originates from leather tanning and paint industries [12], while copper (Cu) is often released through mining and ore processing activities [14]. Lead-acid battery recycling facilities are recognized as a major global source of Pb contamination in surrounding soils [15]. Waste battery recycling is one of the main sources of lead pollution in soil [16].

In our study area, the primary causes of soil contamination by heavy metals are poor technological practices, low-cost and substandard equipment, and improper transportation and handling. Contaminated soil in industrial zones poses a significant risk to the local ecosystem. Therefore, this study aims to determine the distribution patterns, chemical forms, and levels of heavy metals in the soil and to evaluate the potential ecological risks, with the goal of identifying optimal remediation strategies.

2. RESEARCH METHODS

The study area is located in the Nalaikh District, in the southeastern part of Ulaanbaatar city, where a lead-acid battery recycling plant was established in 2024.

The research samples were collected in 2023 and 2024. A total of 78 soil samples were collected to assess heavy metal contamination. For horizontal distribution, 54 samples were taken from 9 locations within the industrial area (0–10 cm depth, 6 replicates per point), and 6 control samples from an undisturbed site located 1000 meters upwind. For vertical distribution, 18 samples were collected from a depth of 0–60 cm at specified intervals, including control samples.

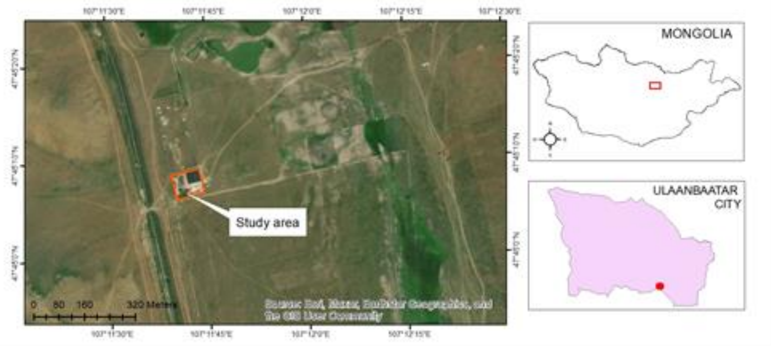

Figure 1. Study area location map

2.1 Analytical procedures

Metal analysis was performed at the SGS laboratory in Ulaanbaatar using ICP-MS and ICP-OES. Soil samples were digested with a mixture of acids (HCl, HF, HNO_3, $HClO_4$) at 220 ± 10°C for 3–4 hours. After evaporation, the residue was further treated with HCl and HNO_3. Certified reference material (CGL-302) was used to ensure accuracy and evaluate the laboratory's performance.

2.2 Chemical Fraction of Metals

Soil metal fractions were determined using the 4-step BCR method, which separated mobile, reducible, oxidizable, and residual forms. Acid-soluble fractions indicate metal mobility and bioaccumulation potential.

2.3 Geoaccumulation index

The Geo-accumulation Index (Igeo), introduced by [17], helps assess environmental pollution by comparing current metal levels with pre-industrial levels. It identifies anthropogenic influence and classifies contamination into seven categories, ranging from uncontaminated (Igeo ≤ 0) to very high contamination (Igeo > 4). The index was calculated using the formula [18].

$$Igeo = log_2 \, Cn/1.5Bn \qquad (1)$$

Cn- measured concentration in the sample (mg kg^{-1}), Bn-Natural background geochemical; 1.5 (mg kg^{-1}).

The Enrichment Factor (EF) is used to assess the extent of human-induced pollution in soils. It classifies contamination into six levels, from no enrichment (EF < 1) to very severe enrichment (EF = 25–50). EF is calculated by normalizing heavy metal concentrations to aluminum in both sample and background soils using Equation (2) [19].

$$EF = \left(\frac{HMs}{AIs}\right) / \left(\frac{HMb}{Aib}\right) \qquad (2)$$

HMs- concentration in the sample mg kg-1, AIs-aluminum are the levels in the sample mg kg -1, HMb-concentration in the background mg kg-1, AIb-aluminum are the levels in the background mg kg-1.

2.4 Statistical analyses

The main statistical parameters (maximum value, mean, standard deviation) were determined using the Pivot Table function in Microsoft Excel. Figures and graphs were created using OriginPro 2024.

3. RESULT AND DISCUSSION

In the soil samples from the study site, the concentrations of heavy metals (Cr, Cu, Ni, Zn, Co, Cd) were within the permissible limits set by the Mongolian soil contamination standard [20]. However, the levels of some metals, particularly Cu and Zn, were found to be twice as high compared to the control soil. The average concentration of arsenic (As) exceeded the standard by 10.2 mg/kg, while the concentration of lead (Pb) exceeded all thresholds tolerable, hazardous, and dangerous with the highest value surpassing the dangerous level by 687 mg/kg (Figure 2).

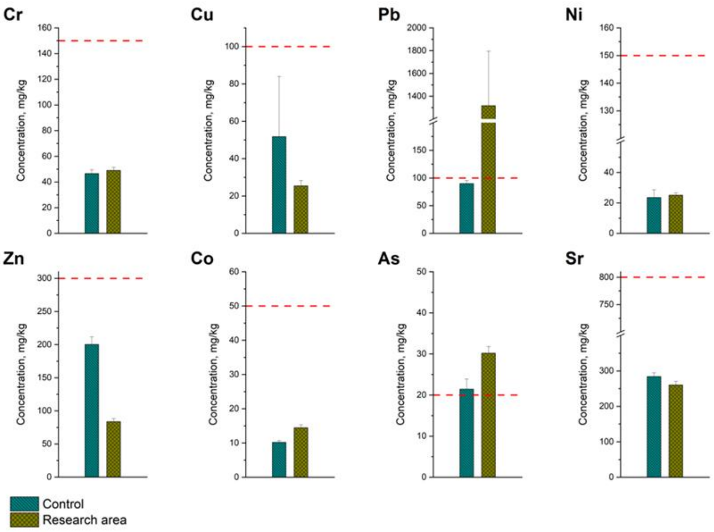

Figure 2. The average concentration of heavy metals in soil (n=60) is shown. The horizontal dashed red line represents the soil standard of Mongolia

Pb is a highly persistent metal in the environment, remaining in soil for extended periods without degradation. It poses a particularly high risk to children's health [21]. Major sources of Pb contamination include waste battery and accumulator recycling facilities [16]. Lead contamination in Ulaanbaatar's soil has reached a level of national concern. The average Pb concentration in urban soil is 39.1 mg/kg, which is twice as high as the rural average of 18.6 mg/kg [22].

Since our study site is located near an accumulator recycling plant, the high Pb contamination is likely due to poor technological practices, low-quality equipment, and improper transportation. A previous study found Pb concentrations ranging from 100 to 143 mg/kg in the central part of Ulaanbaatar, exceeding the MNS 5850:2019 standard [23]. According to the results of similar studies, the concentration of lead found in the soil inside factory premises was on average 22 times higher than in the surrounding environment, with mean concentrations reaching 2500–2600 mg/kg [4], [15]. In our study, the average lead concentration detected in the mixed surface soil samples was 13 times higher compared to the control site soil, indicating a relatively high level of lead contamination in the study area.

During the assessment of the horizontal distribution of heavy metals in the soil, we found that the concentration of lead (Pb), in particular, exceeded standard levels. Therefore, we investigated the vertical distribution (depth variation) of lead in the soil. The analysis revealed that the concentration of lead at a depth of 0–5 cm was 5261.3 mg/kg, which is extremely high and 52.6 times greater than the standard limit (Figure 3.). However, at depths below 5 cm, lead concentrations remained stable and did not exceed standard thresholds. This finding is consistent with international studies [24], which indicate that lead contamination resulting from anthropogenic activities tends to accumulate primarily in the surface layer of the soil, with concentrations decreasing with depth.

After determining the horizontal and vertical distribution of heavy metals in the soil, we proceeded to identify the chemical fractions in which these metals occur. The results revealed that over 50% of Cr (85.2%), Cu (81.4%), Mn (52.5%), Sr (85.8%), Zn (75.0%), Co (72.0%), and As (68.4%) were found in the stable, immobile residual fraction (Figure 4).

This indicates that these elements have low biological availability and thus pose relatively low environmental risk. In contrast, Pb (64.2%) and Cd (32.2%) were predominantly associated with the reducible fraction, bound to iron (Fe) and manganese (Mn) oxides.

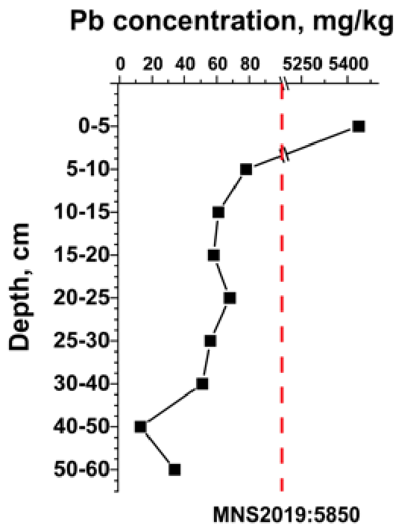

Figure 3. Heavy Metal Content by Soil Depth (n=18) is shown. The vertical dashed red line represents the soil standard of Mongolia

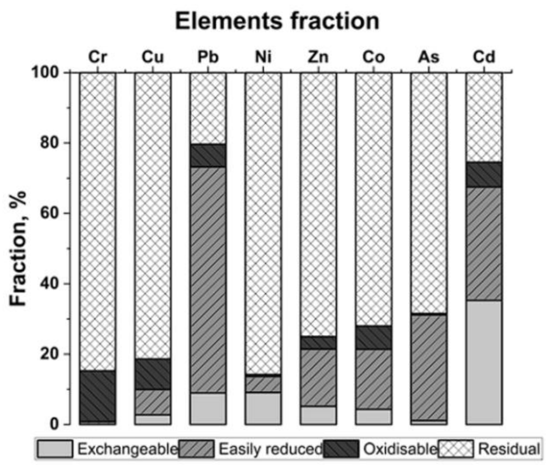

Figure 4. Heavy metals fraction content by 0-10 cm in soil (n=9)

This suggests a higher degree of mobility and, consequently, a greater potential ecological risk. These results are also supported by international studies. For example, a study conducted in the northern part of Guangxi Province, China, found that Pb, Mn, and Zn primarily existed in weakly acid-extractable and thus more mobile forms, indicating the potential to pose significant ecological risks to soil ecosystems [25].

A detailed study of the vertical distribution and chemical fractions of heavy metals is a key feature and

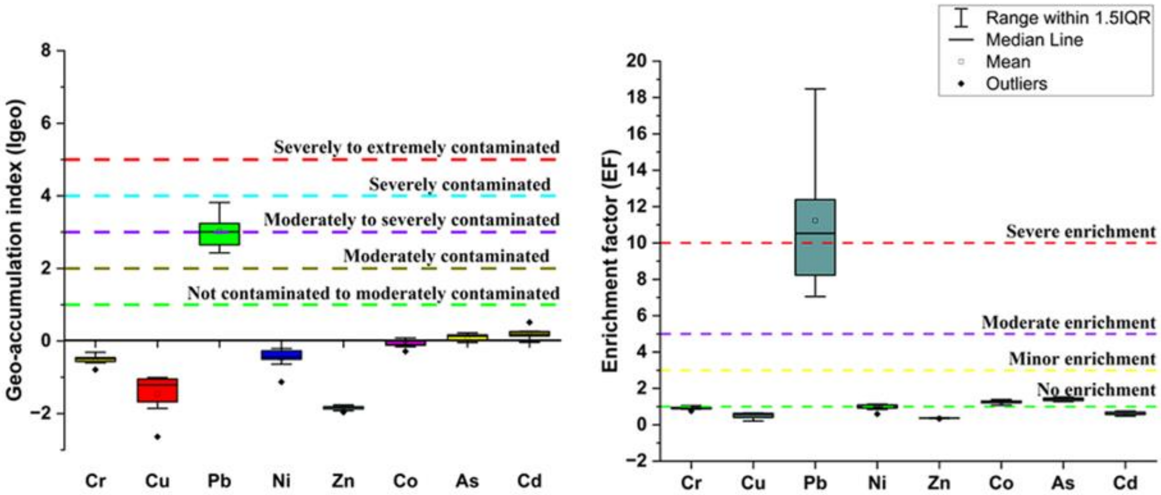

Figure 5. Box plot of Geo-accumulation index (Igeo) and Enrichment factors (EF) of heavy metals in soil (n=54)

novel aspect of this research. The results revealed that lead (Pb) is concentrated in the surface layer of the soil and does not penetrate deeply, which is consistent with findings from international studies. Additionally, the identification of the chemical forms (fractions) of heavy metals showed that Pb and Cd are predominantly present in highly mobile fractions, making them soluble in aqueous environments and indicating a high potential ecological risk. These findings provide important information for pollution impact assessment, risk evaluation, and the development of remediation strategies.

The Geoaccumulation Index (Igeo) and Enrichment Factor (EF) are widely used indicators for assessing the accumulation and intensity of anthropogenic (human-induced) heavy metal pollution on soil surfaces. In our study, the Igeo values for all metals except lead (Pb) fell within the range of $0 < \text{Igeo} \leq 1$, classifying them as "unpolluted to moderately polluted." In contrast, the Igeo values for Pb ranged from 0.77 to 3.45, indicating categories of "moderately to heavily polluted" and "heavily polluted” (Figure 5.).

Regarding the Enrichment Factor (EF), values within the range of $0.5 \leq \text{EF} \leq 1.5$ indicate that a metal is likely derived from natural weathering processes. EF values greater than 1.5 suggest anthropogenic sources [23]. In our study, Pb showed the highest EF value of 18.7, placing it in the "significant enrichment" category ($5 < \text{EF} < 20$), reflecting strong anthropogenic pollution. The order of contamination, based on decreasing EF values, is: Pb > As > Co > Ni > Cr > Cd > Cu > Zn (Figure 5.).

4. CONCLUSION

As a result of the soil contamination study conducted around the battery recycling plant located in Nalaikh District, it was determined that the concentration of lead (Pb) exceeds the permissible limit set by the MNS 5850:2019 standard by several times. Additionally, Pb was predominantly found in the chemically mobile fraction, indicating a potentially high risk to both the environment and human health. The Pb contamination originates from anthropogenic activities and is strongly accumulated in the soil. The research successfully fulfilled the initial objectives, which were to: Determine the concentration of heavy metals, Assess their horizontal and vertical (depth-dependent) distribution in the soil, and Identify their chemical fractions and evaluate the associated environmental risks. The study provides a comprehensive understanding of the pollution levels, sources, distribution patterns, and ecological risks in the investigated area. Therefore, it is essential to implement appropriate remediation technologies to reduce soil contamination and restore soil quality.

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