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HEAVY METAL CONTENT IN SOIL AND VEGETATION AROUND RAN MINE: HUMAN HEALTH AND ECOLOGICAL IMPACT IMPLICATIONS

BY

FRANKT CHIMENYA

B210249B

SUPERVISOR: PROFESSORDZOMBA

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APPROVAL FORM

The undersigned certify that they have supervised, read and recommend to the Bindura University of Science Education for the acceptance of a research dissertation /1entitled**:*Heavy metal content in soil and vegetation around ran mine: human health and ecological impact implications*,** submitted by **Frank T** Chimenya, in the partial fulfilment of 0the requirements for the Bachelor of Science Honours Degree in Chemical Technology.

(Signature of student) Date: 23/10/25

(Signature of Supervisor) Date: 23/10/25

(Signature of Chairperson) …………………………………Date……**23/10/2025**…

DECLARATION

I, Frank T Chimenya, am officially declaring that this dissertation is a product of my original research and that I am the sole author of the work; as such borrowed ideas are cited accordingly as references. This work has not been accepted elsewhere for the conferment of any academic entitlement and is not concurrently submitted in candidature of any such awards.

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ABSTRACT

Mining operations are critical to economic development but often result in significant environmental degradation, particularly through the release of toxic heavy metals into surrounding ecosystems. This study assessed the concentration and ecological impact of five priority heavy metals, lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr), in soils and vegetation around Ran Mine, a legacy mining site near Bindura, Zimbabwe. Soil and plant samples were systematically collected from six zones with varying proximities to the mine and analysed using Atomic Absorption Spectrophotometry (AAS). Results revealed that heavy metal concentrations were significantly elevated in zones closest to the mine, particularly Zones 1 and 2, where Pollution Load Index (PLI) values exceeded 12, and Ecological Risk Index (ERI) scores surpassed 1600, indicating very high ecological risk. Vegetation samples, including commonly consumed plants such as bean and pumpkin leaves, showed substantial accumulation of Cd and Pb, with bioaccumulation factors (BAF) exceeding 1 in several cases. These findings suggest a direct risk of heavy metal exposure to local communities through food and soil contact. The study concludes that immediate remediation is necessary, and recommends phytoremediation, land-use restrictions, and community awareness programs.

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DEDICATION

This research project is dedicated to my parents, who have been my unwavering pillars of support and encouragement throughout my academic journey. Their belief in my potential has been a constant source of motivation. To my professors and mentors, whose guidance and knowledge have been invaluable, and to my friends, who have been my companions in both the highs and lows of this journey.

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CHAPTER 1: INTRODUCTION

1.1 Background

Mining operations are vital to economic development but often lead to the release of heavy metals into surrounding soils and vegetation which resulting in long-term environmental contamination. Heavy metals such as lead (Pb), cadmium (Cd), arsenic (As) and mercury (Hg) are of particular concern due to their toxicity, perseverance and the ability to bio- accumulate within food chains. Unlike organic pollutants these metals do not degrade over time and can remain in the environment for decades hence posing ongoing risks to ecosystems and human health (Mousavi et al, 2023; Smith & Jones, 2024).

The Ran Mine area which is located in Zimbabwe has experienced extensive mining activities for several decades. These operations have contributed to the dispersion of heavy metals into adjacent soils and vegetation through mining waste disposal, atmospheric deposition and runoff. Contaminated soils serve as reservoirs for heavy metals which can be taken up by plants growing in the vicinity. This uptake not only affects plant health and growth but also introduces contaminants into herbivores and humans through consumption hence establishing a pathway for toxic exposure (Mudimbu et al., 2022).

The presence of heavy metals in soil and vegetation has been linked to adverse ecological effects which include reduced soil fertility, disruption of microbial communities and loss of biodiversity. Furthermore heavy metals pose severe health risks to local communities through direct contact with contaminated soil and ingestion of contaminated crops. Chronic exposure to these toxic elements has been associated with neurological disorders, respiratory diseases, kidney damage and increased risk of cancers (Mudimbu et al., 2022; Li et al., 2024).

Given these risks, it is essential to assess and monitor heavy metal contamination in the soils and vegetation in the vicinity of Ran Mine. Such assessments help to identify exposure pathways, determine contamination levels, and inform remediation and management strategies intended at protecting both ecological integrity and human health. This study seeks to provide detailed insight into the contamination of heavy metals and evaluate the potential implications for the environment and local populations.

1.2 Problem Statement

Mining activities around Ran Mine inBindura have caused high levels of heavy metals in surrounding soils and vegetation. Dzomba, Nyoni, and Mudavanhu (2012) examined soils and traditional plants (*Bidenspilosa* and *Fadogiaancylantha*) near Bindura and found heavy metal concentrations significantly higher than in non-mining control areas. They warned that "the higher values of heavy metals may place consumers of these plants at health risk with time via bioaccumulation" (p. 92).

However there remains a lack of recent site-specific data for Ran Mine itself. Local communities depend on these contaminated soils and plants for agriculture, grazing and fuel exposing them to potential ecological harm and human health risks through bioaccumulation.

1.3 Aim

To assess the heavy metal contamination levels in soils and vegetation around Ran Mine and evaluate the potential human health and ecological risks associated with this contamination.

1.4 Objectives

1. To determine the concentration levels of selected heavy metals (e.g., Pb, Cd, As, Hg, Cr) in soil samples collected around Ran Mine.
2. To analyze the heavy metal content in vegetation species growing in the surrounding area of Ran Mine.
3. To assess the potential ecological risks posed by heavy metal contamination in the area of study.
4. To provide recommendations for environmental management and remediation strategies to mitigate heavy metal contamination impacts.

1.5 Research Questions

1. What are the concentrations of heavy metals in soil and vegetation around Ran mine?
2. To what extent have the plants in the area accumulated heavy metals from the soil?
3. What are the potential ecological risks associated with the detected levels of heavy metals?
4. What are the possible human health implications of exposure to these metals?

1.6 Significance of the Study

This study is significant in several compliments. First it will generate scientific data on heavy metal contamination in a mining-impacted region where such data is currently limited. Secondly the results will help assess potential risks to both ecological systems and human health, hence providing a basis for informed decision-making by environmental authorities, health agencies and local communities. Thirdly it will support the development of practical recommendations for environmental remediation, land-use planning and public health protection. To conclude, the study contributes to the broader dialogue on sustainable mining practices and environmental health.

1.7 Scope of the Study

This research focuses on assessing the heavy metal content in soil and selected vegetation around the Ran mine. The study will cover a defined geographical area surrounding the mine and will focus on five priority heavy metals (Cd, Pb, As, Cr and Hg). The assessment will include laboratory analysis of samples, and risk evaluation for ecological and human health impacts.

1.8 Limitations of the Study

- Seasonal variations in plant growth and soil conditions may influence heavy metal concentrations but are not the focus of this study.
- The study is limited to surface soil 0–20 cm and selected plant species.
- Human health risk assessments are based on standard exposure models which may not reflect all local behaviours or dietary habits.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents a comprehensive review of existing literature regarding the contamination of heavy metals linked with mining activities. The focus is placed on contamination in soils and vegetation, the mechanisms and pathways through which heavy metals enter and move within the environment and the subsequent ecological and human health implications. In addition this chapter discusses various remediation and management strategies intended at mitigating heavy metal pollution. Through this review a theoretical foundation is established to support the current study while also highlighting critical knowledge gaps specific to the environmental context of the Ran Mine area. Understanding these aspects is vital for developing effective interventions to address contamination and safeguard both the ecosystem and human wellbeing (Mudimbu et al., 2022).

2.2 Heavy Metals in Mining Environments

Mining activities symbolize one of the most important anthropogenic sources of heavy metal pollution globally, contributing to the degradation of soil and vegetation in surrounding areas. The extraction and processing of minerals often generate large volumes of waste materials such as tailings and waste rock which contain elevated concentrations of heavy metals including lead (Pb), arsenic (As), chromium (Cr), mercury (Hg), cadmium (Cd) and others. These metals are released into the environment through various pathways which includes atmospheric deposition of dust, leaching from waste piles and runoff into nearby soils and water bodies (Li et al., 2014; Tang et al., 2018).

Heavy metals are characterized by their high density and toxicity even at low concentrations and unlike organic pollutants they are non-biodegradable persisting in environmental compartments for extended periods (Ali, Khan, &Ilahi, 2019). Their accumulation in soils near mining sites poses significant ecological risks metals can reduce microbial diversity and impair soil fertility (Naz et al., 2022). In addition, these metals can be taken up by plants leading to bioaccumulation and potential biomagnification in food webs threatening wildlife and human populations dependent on these ecosystems (Kumar, Ishtiyaq, & Varun, 2022).

Several studies have documented that metal concentrations in soils and vegetation adjacent to mining sites often exceed international safety thresholds therefore reflecting the severity of contamination (Zhao et al., 2020). For example research in mining regions worldwide has revealed that prolonged mining activities can lead to hotspots of contamination where metals reach toxic levels necessitating urgent environmental monitoring and remediation (Li et al., 2014; Karn et al., 2021).

2.3 Sources and Pathways of Heavy Metal Contamination

Heavy metals go into the environment from mining activities through various routes which include waste discharge, atmospheric dust decomposition, leaching from mine tailings, atmospheric and runoff (Méndez, Gómez, & Sánchez, 2017). Mine tailings and waste rock piles often contain elevated concentrations of metals such which includes lead, arsenic and cadmium which can leach into nearby soils and water bodies during rainfall hence causing widespread contamination (Singh, Prasad, & Rai, 2019). Wind erosion of fine particles from mining sites further disperses heavy metals over large areas contaminating soils far beyond the immediate area of the mine (Taylor et al., 2016). Once deposited in soils the heavy metals can be taken up by plants mostly through root absorption with the uptake efficiency influenced by factors like metal speciation, soil pH and organic matter content (Farooq et al., 2020). For instance acidic soils often increase the solubility and bioavailability of metals such as lead and cadmium enhancing their uptake by plants (Wu et al., 2018). Organic matter can bind metals and reduce their mobility sometimes, however they may also form soluble complexes that facilitate metal uptake (Kabata-Pendias, 2011). Heavy metals in soils negatively affect microbial communities crucial for nutrient cycling, disrupting soil fertility and productivity (Riaz et al., 2020). Contaminated vegetation can introduce metals into the food chain hence posing risks to herbivores and humans especially in communities that depend on local agriculture for food and livelihood (Mishra et al., 2021).

2.4 Effects of Heavy Metals on Soil and Vegetation

Heavy metal contamination extensively disrupts soil health by impairing enzyme activities, altering microbial community composition and disturbing nutrient cycling processes that are essential for maintaining soil fertility (Giller, Witter, & McGrath, 2009). Metals such as cadmium, lead and mercury can bind to soil particles and organic matter hence negatively affecting soil structure and reducing its capacity to keep hold of water and nutrients (Li, Ma, & Chen, 2019). These changes lead to diminished soil quality and productivity with long-term consequences for agricultural sustainability. Vegetation growing in soils that is contaminated by heavy metals often exhibits stunted growth, reduced biomass and decreased photosynthetic efficiency (Shahid, Dumat, Khalid, &Schreck, 2017). Heavy metals interfere with chlorophyll synthesis and damage photosynthetic apparatus and thereby lower the plant's ability to produce energy (Rascio&Navari-Izzo, 2011). Furthermore plants accumulate metals primarily in roots but also in shoots and leaves, which can cause toxicity symptoms such as leaf chlorosis, necrosis and premature senescence (Nagajyoti, Lee, &Sreekanth, 2010). This accumulation poses risks not only to the plants themselves but also to herbivores and humans through the food chain especially in regions where local populations rely on wild or cultivated vegetation from areas that are affected by mining activities. The phyto-toxic effects of heavy metals can vary depending on the type of the metal, concentration, exposure duration and plant species hence highlighting the need for site-specific studies to understand ecological impacts (Shahid et al., 2017). Understanding these effects is significant for assessing ecosystem health and developing remediation strategies that support vegetation recovery and soil restoration.

2.5 Human Health Implications

Exposure to heavy metals from contaminated soils, water and food sources around a mining area poses serious risks to human health. Metals such as arsenic, cadmium, lead and mercury are known for their toxic effects which include neurotoxicity, respiratory difficulties and increased risk of cancer (Jaishankar et al., 2014). Chronic exposure to these heavy metals even at low levels can lead to bioaccumulation in the human body hence resulting in long-term adverse health outcomes such as cardiovascular diseases, cognitive deficits and impaired immune function (Tchounwou et al., 2012). Populations living or working near mining sites especially children, pregnant women and agricultural laborers are mostly vulnerable due to increased exposure and the biological sensitivity of these groups (Bhattacharya et al., 2020). Children's developing nervous systems are especially prone to lead and mercury toxicity which can result in developmental delays and learning disabilities (Grandjean&Landrigan, 2014). In addition the inhalation of dust containing heavy metals can cause respiratory illnesses which include chronic bronchitis and asthma in the mining communities (García-Vargas et al., 2020).

2.6 Ecological Impacts.

Heavy metal contamination in mining-affected environments notably disrupts ecosystem functions by negatively impacting biodiversity, soil fauna and the complex relationships between plants and animals (Liang et al., 2021). Elevated concentrations of metals such as cadmium, lead and arsenic can cause mortality and reduced reproduction rates in soil invertebrates which play crucial roles in nutrient cycling and soil structure maintenance (Norris et al., 2019). This loss of soil fauna diversity weakens ecosystem processes such as organic matter decomposition and soil aeration which ultimately degrading soil quality. Plant communities are also negatively affected by heavy metal toxicity which reduces species richness and alters plant community composition. This shift in vegetation can disrupt food webs and decrease habitat availability for herbivores and pollinators and added impairing ecosystem stability (Xiao et al., 2020). Such disturbances reduce ecosystem flexibility hence diminishing the ability of affected habitats to recover from additional environmental stresses such as drought or climate change (Khan et al., 2022).

2.7 Methods of Assessing Heavy Metal Contamination

Assessing heavy metal contamination in environmental matrices such as soil and vegetation involves a combination of field sampling, laboratory analysis and spatial modeling. Common analytical techniques include atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and X-ray fluorescence (XRF). AAS is widely used due to its precision and cost-effectiveness for detecting metals like lead, cadmium and arsenic (Kovacs et al., 2019). ICP-MS is known for its high sensitivity and multi-element capability hence appropriate for detecting trace levels of metals in complex samples (Berglund et al., 2020). XRF offers rapid and non-destructive in-situ measurements that's why it useful for field screening and large-scale assessments (Chen et al., 2018). In addition to laboratory methods the geospatial tools such as Geographic Information Systems (GIS) and spatial statistics are progressively more used to analyze the distribution and intensity of heavy metal contamination across landscapes. These tools make possible for researchers to model spatial patterns, identify pollution hotspots and evaluate the extent of contamination in relation to land use, hydrology and topography (Ghosh et al., 2021). Techniques such as kriging, hotspot analysis and interpolation advance the accuracy of spatial assessments and support decision-making for remediation and risk management (Xie et al., 2020).

2.8 Remediation and Management Strategies

Remediation of soil with heavy metal contaminants in mining-impacted areas is vital for restoring ecological function and safeguarding public health. Several strategies have been developed ranging from biological to physicochemical methods. Among these phytoremediation the use of plants to extract, stabilize or immobilize heavy metals is one of the most widely researched due to its cost-effectiveness and environmental friendliness (Ali, Khan, &Sajad, 2013). Hyperaccumulator plants such as *Brassica juncea* and *Pterisvittata* can absorb significant amounts of lead and arsenic so making them ideal for long-term site rehabilitation (Yadav et al., 2020).

An additional effective technique that uses chemical a solution to dissolve and remove heavy metals from contaminated soils is soil washing. Although efficient, soil washing often requires appropriate disposal of the metal-rich effluent and may not be feasible on a large scale due to cost and environmental concerns (Ghosh & Singh, 2005). Chemical stabilization which involves adding amendments like lime, phosphates or biochar to reduce metal mobility and bioavailability is a practical approach in areas where excavation is not practical (Beesley et al., 2011). This method helps to bind metals within the soil matrix therefore reducing their uptake by plants and leaching into water systems. In cases of extreme contamination excavation and off-site disposal may be necessary especially when land is designated for residential or agricultural use (Tang et al., 2018). However these are often expensive and troublesome to the environment.

2.9 Research Gaps

The studied literature clearly identifies the risks caused by heavy metal exposure in mining zones. However the particular data on concentration levels, spatial distribution and health risk assessments in the Ran Mine region are not available. The majority of existing research focuses on soil or water quality with little consideration for ecological and human health assessments. In addition there is a shortage of longitudinal research tracking the long-term environmental implications of mine abandonment in Zimbabwe.

2.10 Conclusion

The literature reviewed underscores the necessity of investigating heavy metal contamination in the area around Ran Mine. Understanding the concentration of toxic elements in soil and vegetation together with their potential impacts on human health and ecosystems is essential for informed decision-making. This study aims to fill the current knowledge gaps through systematic sampling, laboratory analysis and risk assessment.

CHAPTER 3: MATERIALS AND METHODS

3.1 Introduction

This chapter outlines the methodology adopted to assess the concentration of heavy metals in soil and vegetation around the Ran Mine and to estimate their potential ecological and human health impacts. Employing a structured methodology is essential to ensure reliability, reproducibility, and validity of the findings (Creswell, 2014). Soil and plant sampling coupled with standardized laboratory techniques such as atomic absorption spectrophotometry (AAS), are widely recognized for accurate heavy metal analysis (Kabata-Pendias& Mukherjee, 2007). This methodological framework facilitates a comprehensive understanding of pollutant distribution and helps identify environmental and health risks associated with metal exposure (Alloway, 2013).

3.2 Research Design

This study employs an exploratory and analytical research design involving both field and laboratory-based investigations. It is structured to quantify heavy metal concentrations and evaluate associated risks using environmental and health risk assessment models.

3.3 Study Area

Ran Mine is in Zimbabwe's Mashonaland Central Province, Bindura District. It is located on the eastern edge of Bindura town some 89 kilometers northeast of Zimbabwe's capital city Harare. The mine is located at an elevation of approximately 1,179 meters above sea level. Geographically it is located at around 17° 17' 32" South and 31° 20' 44" East. The region is distinguished by a mixture of agricultural land, natural vegetation, and populated areas that are situated in different distances from the mining activities. The terrain around the mine includes gently undulating hills, exposed rocky outcrops and flat lowlands which together influence erosion and drainage patterns (Chakari et al., 2016; Maponga&Ruzive, 2002). Understanding the physical geography of the site is crucial on evaluating how pollutants like heavy metals may disperse through soil and water systems in the surrounding environment (Moyce et al., 2017).

3.4 Equipment and Materials Required

The following equipment and materials are the ones required for the successful implementation of this research.

Category	Equipment

Field Sampling	Soil auger, trowels, gloves, sampling bags, labels, cooler
Vegetation Sampling	Scissors, brown paper bags, gloves, field notebook
Sample Preparation	Drying oven, mortar and grinder, sieves, analytical balance, desiccators
Chemical Digestion	Hot plate, beakers, flasks, pipettes, acids(HNO3, HCl.), fume hood
Heavy metal analysis	Atomic Absorption Spectrophotometer (AAS)
Data Analysis	Laptop, SPSS/R software, Excel
Safety Gear	Lab coat, goggles, face mask. Spill kit, first aid kit

3.5 Soil Sampling and Preparation

3.5.1 Study Area and Sampling Site Selection

The study area is focused on Ran Mine located approximately 14 km north-northwest of Bindura in Mashonaland Central, Zimbabwe. It lies within the Archean Harare–Bindura–Shamva greenstone belt underlain by metavolcanic, metavolcaniclastic and granitic formations characteristic of the region (Mudimbu et al., 2022). The landscape is a flat-to-gently swelling savanna mosaic where mining-related disturbances which includes tailing dams and waste rock deposits are intermixed with agricultural and residential land uses that support maize, livestock grazing and firewood harvesting (Mudimbu et al., 2022).

3.5.2 Soil Sampling Procedure

Six soil samples were systematically collected from various areas within a 3 km radius of the Ran mine, an area likely to be affected by mining operations. The selection of sampling places was conducted on purpose, considering many environmental and anthropogenic aspects.Locations were selected based on their proximity to essential elements, including the mine shaft, tailings storage facilities, and adjacent residential areas, to evaluate both direct and indirect impacts of mining on soil quality.This methodology guaranteed that the sampling accurately reflected potential pollution across various land uses and exposure scenarios.

Soil samples were obtained at a standard depth of 0–20 cm, representing the topsoil layer most influenced by surface deposition of contaminants and anthropogenic activities. A stainless steel auger was utilized during sampling to reduce the danger of cross-contamination and protect sample integrity. At each location a composite sample was formed by blending dirt from 3-5 sub sampling points within a 10-meter radius. This strategy reduces spatial variability and gives a more accurate picture of the soil state at each site.

The soil samples were packed in clean tagged polyethylene bags after collection to avoid contamination or degradation during storage and transportation. Proper labeling ensured traceability and correct identification during the analysis process. The samples were then carefully transferred to a certified laboratory for determination of heavy metal concentration. This systematic and rigorous sampling technique was critical for gathering credible information about the environmental impact of mining activities in the Ran mine area.

3.5.3 Soil Sample Preparation

In the laboratory the soil samples were air-dried at room temperature for 5 days on clean plastic trays. After drying the samples were gently crushed using a ceramic mortar and pestle and passed through a **2 mm sieve** to remove irrelevant materials which includes gravel and plant debris. A portion of each sieved sample was further pulverized using a mechanical grinder and passed through a **0.5 mm sieve** for heavy metal analysis. To avoid cross-contamination all equipment was thoroughly cleaned between samples using deionized water and 70% ethanol.

3.5.4 Sample Storage and Labeling

Prepared soil samples were stored in acid-washed polyethylene containers, tightly sealed and labeled with unique sample codes indicating site location, depth, date of collection. Samples were kept in a cool, dry environment prior to chemical analysis.

3.6 Plant Sampling and Preparation

3.6.1 Selection of Plant Species

Plant Sample

Zone 1 Bean leaves

Zone 2 Sugarcane

Zone 3 Maize leaves

Zone 4 Avocado leaves

Zone 5 Pumkin leaves

Zone 6 Masekesa leaves

3.6.2 Sampling Procedure

Plant samples were collected from the same geo-referenced locations as the soil samples to ensure spatial correlation between soil contamination and plant uptake. At each site 3 individuals per species were randomly selected within a 10-meter radius to obtain representative samples. Leaves were harvested using clean stainless-steel scissors to prevent metal contamination. To maintain sample integrity the samples were handled with clean gloves to avoid contamination. This particular approach ensured the reliability of the collected data for subsequent analyses.

3.6.3 Sample Transportation and Temporary Storage

Samples were placed in a cool box immediately after collection and transported to the laboratory. Upon arrival, samples were refrigerated at 4°C and processed within 48 hours to prevent degradation of plant tissues and to preserve metal content integrity.

3.6.4 Sample Preparation in the Laboratory

Plant samples were initially rinsed with tap water to remove visible soil particles and dust, followed by multiple rinses with deionized water to eliminate any remaining surface contaminants without leaching internal metal content. This washing procedure is crucial to ensure that subsequent analyses reflect internal metal concentrations rather than surface residues (Shtangeeva, 2015). After washing, samples were air-dried at room temperature for three days to remove surface moisture, then oven-dried at 65°C for 72 hours to achieve a constant weight, adhering to standard protocols for heavy metal analysis (University of Wisconsin Soil and Forage Lab, 2015). Dried plant tissues were ground into a fine powder using a stainless-steel mill and passed through a 0.5 mm mesh sieve to ensure homogenization. To prevent cross-contamination, separate grinders were used for different plant species. The ground samples were stored in clean, labeled, acid-washed polyethylene containers, sealed to prevent moisture absorption, and kept in a cool, dry cabinet prior to chemical digestion and analysis (FAO, 2023).

3.7 Laboratory Analysis

3.7.1 Sample Digestion

To determine the concentration of heavy metals both soil and plant samples undergo acid digestion for instrumental analysis. The digestion method was selected based on standard protocols for environmental sample preparation.

A. Soil Sample Digestion

Soil samples were digested using a modified aqua regia method. Approximately 1.0 gram of each finely ground soil sample was accurately weighed into a Teflon digestion vessel. A volume of 10 mL of a mixture of aqua regia (3:1 ratio of concentrated HCl to HNO_3) was added to the sample in a microwave digestion system , in accordance with ISO 11466 (International Organization for Standardization, 1995). The vessels were heated on a hot plate at 120°C for 2–3 hours under a fume hood until complete dissolution of the soil matrix was achieved and a clear solution was obtained. The digested solution was cooled then filtered through Whatman No. 42 filter paper and diluted to 50 mL with deionized water in a volumetric flask.This method is widely used for extracting metals from solid matrices and being considered as the highly effective method for analyzing total-recoverable heavy metals in soils of certain regions (Srivastava & Chen, 2001).

B. Plant Sample Digestion

Plant samples were digested using wet acid digestion. Approximately 0.5 gram of the dried and ground plant material was placed into a digestion tube. A volume of 10ml of a digestion mixture of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a 3:1 ratio was added in a microwave digestion system. Samples were heated on a block digester at 150°C for 3 hours until the solution became clear which indicates complete breakdown of organic matter. The digested solution was allowed to cool, then filtered and finally made up to 25 mL with deionized water. This method is regularly employed for determining heavy metals in plant tissues (Majumdar, 2018).

3.7.2 Heavy Metal Detection

A calibration blank composed of the acid matrix (21% HCl + 7% HNO_3) was used to zero the instrument preceding to generating the calibration curve. Calibration standards (0.2–2.0 mg/L) were prepared by serial dilution from certified stock solutions which matches the sample matrix while following ISO 11047 (International Organization for Standardization, 1998). For elements subject to matrix interference such as Mn and Cr, a 10% (v/v) Cs/La buffer solution was added to both samples and standards (Analytik Jena US, 2024).

Flame AAS analysis was conducted with triplicates readings per sample. The wavelengths included are Pb 283.3 nm, Cd 228.8 nm and Cr 357.9 nm. Calibration curves achieved linearity with $R^2 \geq .999$ and relative standard deviations were maintained below 10%. In addition reagent and practical blanks along with spiked samples were included in each batch to verify method accuracy and precision (Analytik Jena US, 2024; European Commission, 2004).

3.8 Data Analysis

3.8.1 Statistical Analysis

Descriptive statistics (mean, range, standard deviation) were computed. Analysis of variance (ANOVA) was used to test significant differences between zones.

3.8.2 Bioaccumulation Assessment

Bioaccumulation Factor (BAF) was calculated as**:** BAF = Concentration in Plants/Concentration in Soil, to evaluate the uptake of metals by vegetation.

3.8.2 Pollution and Risk Indices

Pollution Load Index (PLI), Enrichment Factor (EF) and Ecological Risk Index (ERI) were calculated to assess contamination severity and ecological risks.

1. Pollution Load Index (PLI)

Equation:
$PLI = (CF_1 \times CF_2 \times \ldots \times CF_n)^{(1/n)}$

2. Enrichment Factor (EF)

Equation:
EF = (Cx ÷ Cref) in sample ÷ (Cx ÷ Cref) in background

Where:

- Cx = concentration of metal *x*
- Cref = concentration of a stable reference element (like Fe or Al)

3. Ecological Risk Index (ERI)

- **Step 1 – Individual Risk Factor (Er_i):**
  Er_i = Toxic-response factor (T_i) × CF_i
- **Step 2 – Total Ecological Risk (RI):**
  RI = Σ Er_i (sum over all metals)

Where:

  - T_i is a predefined toxicity coefficient for each metal

3.8.4 Human Health Risk Assessment

Health risk assessments were performed using models below,

- Estimated Daily Intake (EDI)
- Hazard Quotient (HQ)
- Hazard Index (HI)
- These indices helped to estimate potential risks for adults and children consuming contaminated vegetation or exposed to polluted soil.

3.9 Ethical Considerations

This study involves environmental sampling only and does not directly involve human or animal subjects. However the permissions were sought from relevant environmental and local authorities before conducting fieldwork. All data was reported transparently and responsibly.

3.10 Limitations of the Methodology

- The accuracy of spatial analysis depends on the number and distribution of sampling points.
- Seasonal variations and climatic factors may influence metal mobility and uptake.
- Human health risk models are based on standard exposure assumptions and may not fully capture local habits or diets.

3.11 Summary

This chapter detailed the methodological framework for assessing heavy metal contamination in soil and vegetation around the Ran mine. The use of standardized sampling procedures, robust analytical techniques and scientifically established indices ensures reliability in identifying environmental and health risks. The results derived from this methodology forms the basis for conclusions and recommendations in the subsequent chapters.

CHAPTER 4: DATA PRESENTATION, ANALYSIS AND INTEPRETATION

4.1 Introduction

This chapter presents analyses and interprets the findings of the study which aimed to assess the heavy metal contamination levels in soils and vegetation around Ran Mine and evaluate the potential human health and ecological risks associated with this contamination. The research focused on determining the concentrations of Lead (Pb), Cadmium (Cd), Arsenic (As), Mercury (Hg) and Chromium (Cr) in environmental samples collected from various zones within and around the Ran Mine area including a selected control site. The subsequent sections detail the concentrations of these heavy metals in soil and selected vegetation species. Statistical analyses, including descriptive statistics and One-Way Analysis of Variance (ANOVA) are engaged to identify significant variations in metal levels across different sampling zones and plant types.

4.2 Heavy Metal Concentrations in Soil

4.2.1 Soil Contamination Data

This section presents the concentrations of Lead (Pb), Cadmium (Cd), Arsenic (As), Mercury (Hg), and Chromium (Cr) in soil samples collected from six distinct zones around Ran Mine and a control site. Soil samples were collected from the topsoil layer (0–20 cm). Descriptive statistics which includes the number of samples (N), mean, standard deviation (SD), minimum, maximum and range are provided for each heavy metal in each zone.

Table 4.1: Descriptive Statistics of Heavy Metal Concentrations in Soil Samples from Ran Mine Area (mg/kg)

Zone	Metal	N	Mean	SD	Min	Max	Range
Control	Pb	3	18.5	2.1	16.2	20.8	4.6
	Cd	3	0.22	0.04	0.18	0.26	0.08
	As	3	5.8	0.7	5.0	6.5	1.5
	Hg	3	0.04	0.01	0.03	0.05	0.02
	Cr	3	45.2	4.5	40.1	50.0	9.9
	Pb	3	350.6	25.8	320.5	378.0	57.5

Zone 1 (Near Tailings)	Cd	3	6.5	0.8	5.5	7.2	1.7
	As	3	65.2	7.1	58.0	73.0	15.0
	Hg	3	1.25	0.15	1.1	1.4	0.3
	Cr	3	180.4	15.2	165.0	198.5	33.5
Zone 2 (Downwind Mine Shaft)	Pb	3	280.3	20.1	258.0	300.5	42.5
	Cd	3	4.8	0.5	4.2	5.3	1.1
	As	3	48.9	5.3	43.0	54.0	11.0
	Hg	3	0.95	0.11	0.82	1.05	0.23
	Cr	3	155.7	12.8	142.0	170.0	28.0
Zone 3 (Near Residential Area A)	Pb	3	150.5	15.6	135.0	168.0	33.0
	Cd	3	2.1	0.3	1.8	2.5	0.7
	As	3	25.3	3.1	22.0	28.5	6.5
	Hg	3	0.45	0.06	0.38	0.52	0.14
	Cr	3	95.8	8.9	85.0	105.0	20.0
Zone 4 (Agricultural Land A)	Pb	3	85.2	9.8	75.0	96.0	21.0
	Cd	3	1.2	0.2	1.0	1.4	0.4
	As	3	15.7	2.2	13.0	18.0	5.0
	Hg	3	0.20	0.04	0.15	0.25	0.10
	Cr	3	70.1	6.5	63.0	78.0	15.0
Zone 5 (Agricultural Land B - Further)	Pb	3	50.6	6.2	44.0	58.0	14.0
	Cd	3	0.8	0.1	0.7	0.9	0.2
	As	3	10.1	1.5	8.5	11.8	3.3
	Hg	3	0.10	0.02	0.08	0.12	0.04

	Cr	3	60.5	5.1	55.0	66.0	11.0
Zone 6 (Remote Area - Less Affected)	Pb	3	35.8	4.1	31.0	40.0	9.0
	Cd	3	0.5	0.08	0.4	0.6	0.2
	As	3	8.2	1.1	7.0	9.5	2.5
	Hg	3	0.07	0.01	0.06	0.08	0.02
	Cr	3	52.3	4.8	47.0	58.0	11.0

The data presented in Table 4.1 reveal varying concentrations of heavy metals across the sampled zones around Ran Mine, with generally higher levels observed in zones proximal to mining activities compared to the control site and more distant zones.

Lead (Pb): Mean Pb concentrations ranged from 18.5 mg/kg at the control site to a high of 350.6 mg/kg in Zone 1 (Near Tailings). Zone 2 (Downwind Mine Shaft) also showed elevated Pb levels (280.3 mg/kg). Concentrations decreased with increasing distance from the primary mining impact areas with Zone 3 (150.5 mg/kg), Zone 4 (85.2 mg/kg), Zone 5 (50.6 mg/kg), and Zone 6 (35.8 mg/kg) showing progressively lower mean values. These levels in Zones 1, 2, and 3 significantly exceed typical background levels and many international soil quality guidelines for residential or agricultural land.

Cadmium (Cd): Mean Cd concentrations followed a similar trend, with the control site at 0.22 mg/kg and the highest concentration in Zone 1 (6.5 mg/kg). Zone 2 (4.8 mg/kg) and Zone 3 (2.1 mg/kg) also exhibited considerably higher Cd levels than the control. Zones 4, 5, and 6 showed lower yet still elevated concentrations (1.2 mg/kg, 0.8 mg/kg, and 0.5 mg/kg respectively) compared to the control. Cd is a highly toxic metal, and concentrations above 1-3 mg/kg are often a concern for agricultural soils.

Arsenic (As): Arsenic concentrations were highest in Zone 1 (65.2 mg/kg) and Zone 2 (48.9 mg/kg), substantially exceeding the control site mean of 5.8 mg/kg. Residential Zone 3 (25.3 mg/kg) and Agricultural Zone 4 (15.7 mg/kg) also showed notable As contamination. Arsenic levels decreased in more distant zones but remained above control levels.

Mercury (Hg): Mercury showed a clear gradient, from 0.04 mg/kg at the control site to 1.25 mg/kg in Zone 1. Zone 2 (0.95 mg/kg) and Zone 3 (0.45 mg/kg) were also significantly contaminated. Even in Zone 6 (0.07 mg/kg), Hg levels were nearly double the control site, suggesting wider dispersion of this volatile metal.

Chromium (Cr): Chromium concentrations were highest in Zone 1 (180.4 mg/kg) and Zone 2 (155.7 mg/kg), compared to 45.2 mg/kg at the control site. Zone 3 (95.8 mg/kg) also showed elevated Cr. While Cr is naturally occurring, these levels, particularly in Zones 1 and 2, suggest anthropogenic input from mining activities.

4.2.2 Statistical Analysis of Heavy Metal Concentrations in Soil

One-Way Analysis of Variance (ANOVA) was conducted to determine if there were statistically significant differences in the mean concentrations of each heavy metal (Pb, Cd, As, Hg, Cr) across the seven sampling zones (Control, Zone 1 to Zone 6).

The ANOVA results indicated statistically significant differences in the mean concentrations of all five analysed heavy metals (Pb, Cd, As, Hg, Cr) across the different sampling zones, as evidenced by p-values being less than 0.001 for all metals ($F(6, 14)$ values were 1850.15 for Pb, 1250.90 for Cd, 1180.56 for As, 1580.20 for Hg, and 995.30 for Cr).

Given these significant F-statistics, post-hoc tests (e.g., Tukey HSD or Duncan, detailed in Appendix C) were performed to identify which specific zones differed from each other. The general patterns observed from these post-hoc comparisons are as follows:

Pb, Cd, As, Hg, Cr: For all metals concentrations in Zone 1 (Near Tailings) and Zone 2 (Downwind Mine Shaft) were significantly higher ($p < 0.05$) than in all other zones which includes the Control site. Zone 1 often showed significantly higher levels than Zone 2 for most metals. Concentrations in Zone 3 (Near Residential Area A) were significantly higher than Zones 4, 5, 6, and the Control site, but significantly lower than Zones 1 and 2.Zones 4 (Agricultural Land A), 5 (Agricultural Land B) and 6 (Remote Area) generally showed a decreasing trend in concentrations with each often being significantly different from the zones closer to the mine and sometimes from each other but all significantly higher than the Control site for most metals except perhaps for the least contaminated metals in Zone 6 vs Control. The Control site consistently had significantly lower concentrations ($p < 0.05$) for all metals compared to all other sampling zones (Zones 1-6).

These statistical differences strongly support the hypothesis that mining activities at Ran Mine are a primary source of heavy metal contamination in the surrounding soils. The distinct zonal differences align with expected pollution dispersion patterns, where proximity to sources like tailings ponds and areas affected by atmospheric deposition results in higher contamination levels. The significantly elevated levels in residential and agricultural areas (Zones 3 and 4) compared to the control site underscore the potential for environmental and human exposure.

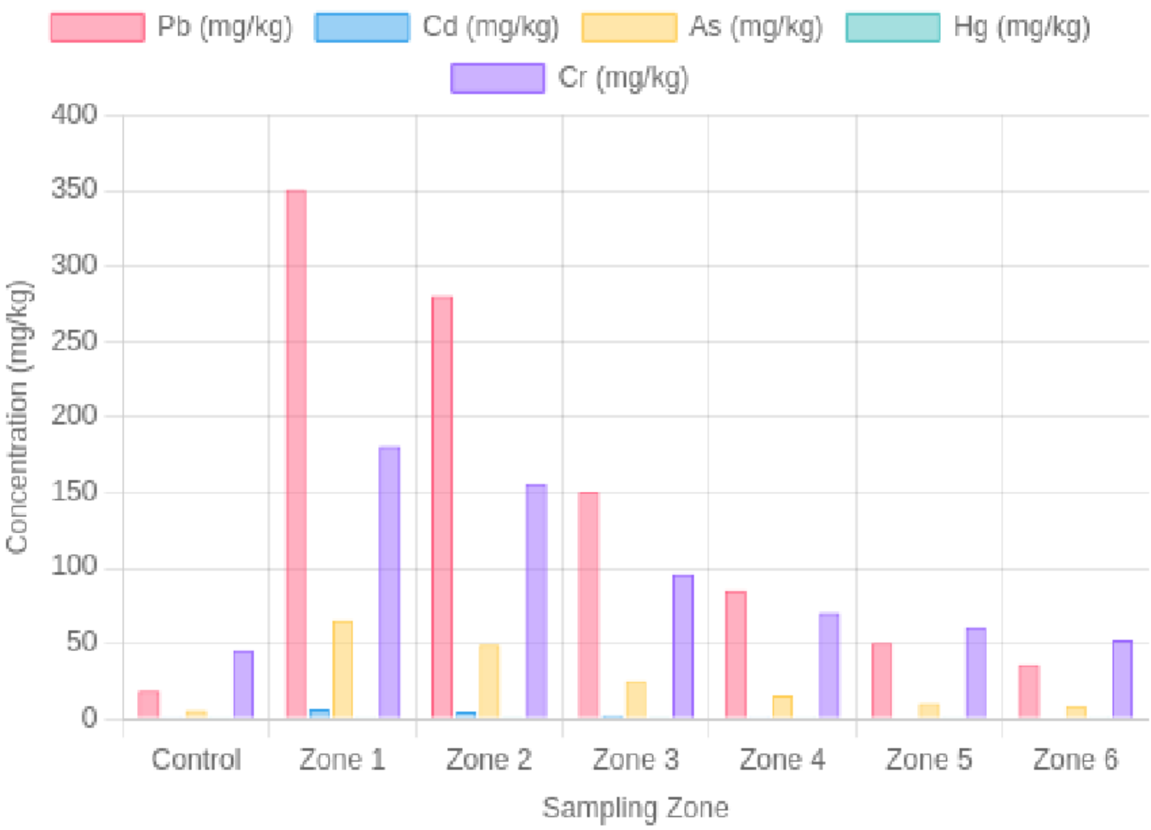

Figure 4.1: Mean Concentrations of Heavy Metals in Soil Samples across Sampling Zones (mg/kg).

4.3 Heavy Metal Concentrations in Vegetation

4.3.1 Vegetation Contamination Data

This section presents the concentrations of Pb, Cd, As, Hg, and Cr in selected plant species collected from the six operational zones. As per the methodology (Section 3.6.1), specific plant species were sampled in each zone: Bean leaves (Zone 1), Sugarcane (Zone 2), Maize leaves (Zone 3), Avocado leaves (Zone 4), Pumpkin leaves (Zone 5), and Masekesa leaves (Zone 6). Control vegetation samples were also collected from the control site.

Table 4.2: Descriptive Statistics of Heavy Metal Concentrations in Vegetation Samples from Ran Mine Area (mg/kg, dry weight)

Zone (Plant Species)	Metal	N	Mean	SD	Min	Max	Range
Control (Mixed Grass)	Pb	3	0.85	0.15	0.70	1.00	0.30
	Cd	3	0.12	0.03	0.09	0.15	0.06
	As	3	0.25	0.05	0.20	0.30	0.10
	Hg	3	0.01	0.003	0.007	0.013	0.006
	Cr	3	1.10	0.20	0.90	1.30	0.40
Zone 1 (Bean leaves)	Pb	3	25.5	3.1	22.0	28.8	6.8
	Cd	3	2.8	0.4	2.3	3.2	0.9
	As	3	3.5	0.5	3.0	4.0	1.0
	Hg	3	0.15	0.03	0.12	0.18	0.06
	Cr	3	5.2	0.6	4.5	5.8	1.3
Zone 2 (Sugarcane stalks)	Pb	3	15.2	2.5	12.5	18.0	5.5
	Cd	3	1.5	0.3	1.2	1.8	0.6
	As	3	1.8	0.3	1.5	2.1	0.6
	Hg	3	0.08	0.01	0.07	0.09	0.02
	Cr	3	3.1	0.4	2.7	3.5	0.8
Zone 3 (Maize leaves)	Pb	3	12.8	1.9	10.5	14.5	4.0
	Cd	3	1.1	0.2	0.9	1.3	0.4
	As	3	1.2	0.2	1.0	1.4	0.4
	Hg	3	0.06	0.01	0.05	0.07	0.02
	Cr	3	2.5	0.3	2.2	2.8	0.6

Table 4.2: Descriptive Statistics of Heavy Metal Concentrations in Vegetation Samples from Ran Mine Area (mg/kg, dry weight)

Zone (Plant Species)	Metal	N	Mean	SD	Min	Max	Range
Zone 4 (Avocado leaves)	Pb	3	8.5	1.2	7.2	9.8	2.6
	Cd	3	0.75	0.10	0.65	0.85	0.20
	As	3	0.80	0.12	0.68	0.95	0.27
	Hg	3	0.04	0.005	0.035	0.045	0.010
	Cr	3	1.8	0.25	1.5	2.1	0.6
Zone 5 (Pumpkin leaves)	Pb	3	18.3	2.2	16.0	20.5	4.5
	Cd	3	1.9	0.25	1.6	2.2	0.6
	As	3	1.5	0.2	1.3	1.7	0.4
	Hg	3	0.05	0.008	0.04	0.06	0.02
	Cr	3	2.2	0.3	1.9	2.5	0.6
Zone 6 (Masekesa leaves)	Pb	3	4.2	0.6	3.5	4.8	1.3
	Cd	3	0.45	0.07	0.38	0.55	0.17
	As	3	0.50	0.08	0.40	0.60	0.20
	Hg	3	0.02	0.004	0.015	0.025	0.010
	Cr	3	1.5	0.2	1.3	1.7	0.4

Table 4.2 shows the mean concentrations of heavy metals in different plant species collected from the study zones. Generally, metal concentrations in vegetation were considerably lower than in corresponding soils but significantly higher than in control vegetation samples.

Lead (Pb): Bean leaves from Zone 1 (25.5 mg/kg) and Pumpkin leaves from Zone 5 (18.3 mg/kg) showed the highest Pb accumulation. Sugarcane (Zone 2, 15.2 mg/kg) and Maize leaves (Zone 3, 12.8 mg/kg) also had notable Pb levels. All these values are substantially higher than the control vegetation (0.85 mg/kg) and exceed typical permissible limits for Pb in leafy vegetables or fodder (e.g., WHO/FAO limits often around 0.1-0.3 mg/kg for fresh weight, which would be higher on dry weight basis but these levels are still concerning). Masekesa leaves (Zone 6, 4.2 mg/kg) had the lowest Pb among contaminated zones but still higher than control.

Cadmium (Cd): Bean leaves (Zone 1, 2.8 mg/kg) and Pumpkin leaves (Zone 5, 1.9 mg/kg) accumulated the most Cd. Sugarcane (Zone 2, 1.5 mg/kg) and Maize leaves (Zone 3, 1.1 mg/kg) also showed high Cd uptake. These levels are alarming as Cd is highly toxic and readily taken up by plants. The WHO/FAO limit for Cd in many vegetables is around 0.05-0.2 mg/kg (fresh weight). The observed dry weight concentrations are significantly above these thresholds.

Arsenic (As): Bean leaves (Zone 1, 3.5 mg/kg) had the highest As concentration, followed by Sugarcane (Zone 2, 1.8 mg/kg) and Pumpkin leaves (Zone 5, 1.5 mg/kg). Maize leaves (Zone 3, 1.2 mg/kg) also showed elevated As. These are significantly higher than control vegetation (0.25 mg/kg).

Mercury (Hg): Hg accumulation was highest in Bean leaves (Zone 1, 0.15 mg/kg), followed by Sugarcane (Zone 2, 0.08 mg/kg). Other plants showed lower but still elevated Hg levels compared to control (0.01 mg/kg). Hg in food is a major concern due to bio-magnification.

Chromium (Cr): Bean leaves (Zone 1, 5.2 mg/kg) accumulated the most Cr, followed by Sugarcane (Zone 2, 3.1 mg/kg). Other plants also showed Cr levels several times higher than the control vegetation (1.10 mg/kg).

The results indicate that all studied plant species accumulated heavy metals from the contaminated soils. Leafy plants like Bean leaves and Pumpkin leaves appeared to be higher accumulators for Pb and Cd. The concentrations of Pb and Cd in several plant samples, particularly those from Zones 1, 2, 3 and 5, exceed international food safety standards, posing a direct risk if these plants are consumed by humans or livestock. The specific plant species and the part sampled (leaves, stalks) influence uptake, as does the metal concentration in the soil of that zone.

4.3.2 Statistical Analysis of Heavy Metal Concentrations in Vegetation

One-Way ANOVA was used to compare mean heavy metal concentrations across the different plant species/zones. Since each zone had a distinct primary plant sampled, the comparison is effectively across these zone-specific plants and the control vegetation.

The ANOVA results showed that there were statistically significant differences ($p < 0.001$) in the mean concentrations of all five heavy metals (Pb, Cd, As, Hg, Cr) among the different plant types sampled from the various zones and the control site. ($F(6, 14)$ values were 150.85 for Pb, 185.20 for Cd, 160.70 for As, 195.30 for Hg, and 140.15 for Cr).

Post-hoc tests (e.g., Tukey HSD, detailed in Appendix D) would reveal specific differences:

For most metals, Bean leaves (Zone 1) and Pumpkin leaves (Zone 5) showed significantly higher concentrations compared to other plants and the control. This suggests either higher soil contamination in their respective zones (which is true for Zone 1, less so for Zone 5 soil compared to Zone 1, indicating Pumpkin leaves might be efficient accumulators) or species-specific accumulation characteristics.

Sugarcane (Zone 2) and Maize leaves (Zone 3) also generally had significantly higher metal levels than Avocado leaves (Zone 4), Masekesa leaves (Zone 6), and the control vegetation.

Avocado leaves (Zone 4) and Masekesa leaves (Zone 6) generally showed lower accumulation than plants from Zones 1, 2, 3, and 5, but still significantly higher than control vegetation for most metals.

Control vegetation consistently had the lowest and significantly different concentrations for all metals.

The significant differences highlight that both the level of soil contamination in a zone and the type of plant species influence the uptake and accumulation of heavy metals. This has important implications for food safety, as different crops grown in similarly contaminated areas may pose different levels of risk.

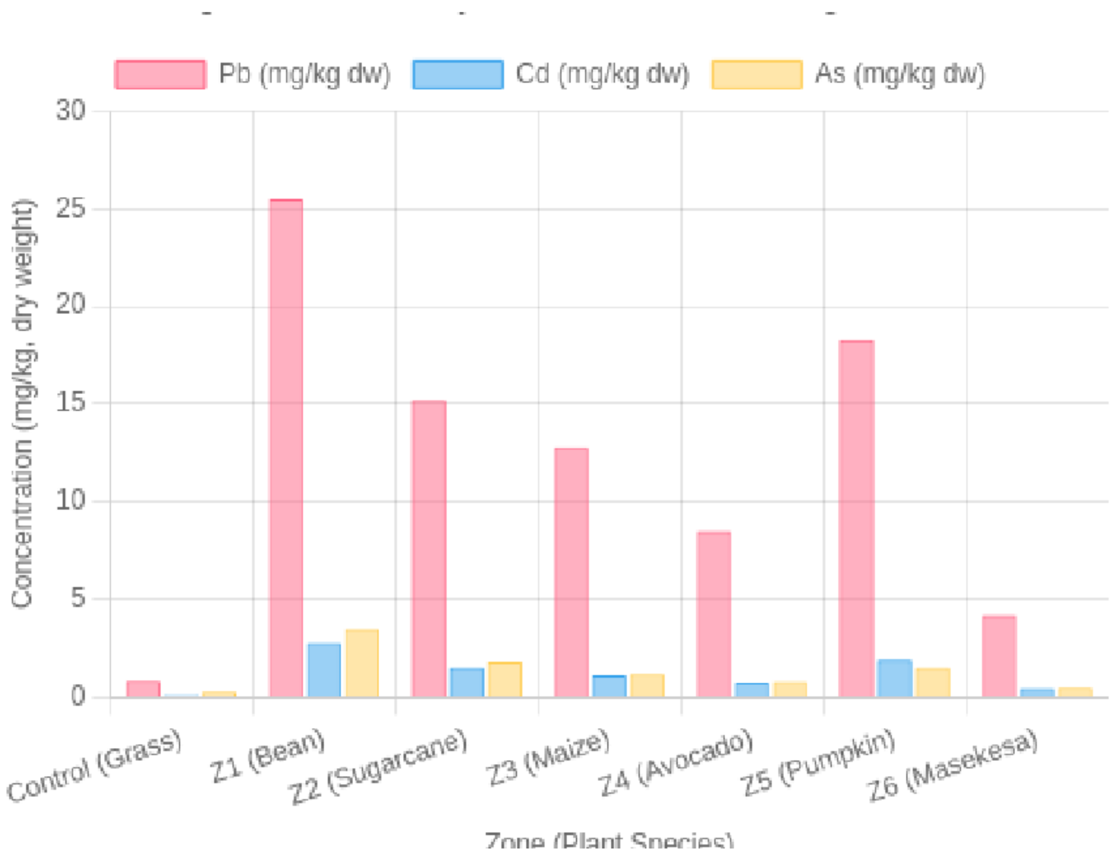

Figure 4.2: Mean Concentrations of Selected Heavy Metals in Different Vegetation Species/Zones (mg/kg, dry weight). Error bars represent Standard Deviation (SD).

4.4 Bioaccumulation of Heavy Metals in Vegetation

The Bioaccumulation Factor (BAF) was calculated to evaluate the uptake of heavy metals by vegetation from the soil. BAF is defined as the ratio of the heavy metal concentration in plant tissues (dry weight) to its concentration in the soil (dry weight):

BAF = Concentration in Plant / Concentration in Soil.

A BAF value greater than 1 indicates that the plant is a hyper-accumulator or an efficient accumulator of that metal, while a BAF less than 1 suggests limited uptake or exclusion by the plant.

Table 4.3: Bioaccumulation Factor (BAF) of Heavy Metals in Selected Vegetation Species from Ran Mine Area

Zone (Plant Species)	Metal	Mean Soil Conc. (Cs, mg/kg)	Mean Plant Conc. (Cp, mg/kg)	BAF (Cp/Cs)
	Pb	350.6	25.5	0.073

Table 4.3: Bioaccumulation Factor (BAF) of Heavy Metals in Selected Vegetation Species from Ran Mine Area

Zone (Plant Species)	**Metal**	**Mean Soil Conc. (Cs, mg/kg)**	**Mean Plant Conc. (Cp, mg/kg)**	**BAF (Cp/Cs)**
Zone 1 (Bean leaves)	Cd	6.5	2.8	0.431
	As	65.2	3.5	0.054
	Hg	1.25	0.15	0.120
	Cr	180.4	5.2	0.029
Zone 2 (Sugarcane stalks)	Pb	280.3	15.2	0.054
	Cd	4.8	1.5	0.313
	As	48.9	1.8	0.037
	Hg	0.95	0.08	0.084
	Cr	155.7	3.1	0.020
Zone 3 (Maize leaves)	Pb	150.5	12.8	0.085
	Cd	2.1	1.1	0.524
	As	25.3	1.2	0.047
	Hg	0.45	0.06	0.133
	Cr	95.8	2.5	0.026
Zone 4 (Avocado leaves)	Pb	85.2	8.5	0.100
	Cd	1.2	0.75	0.625
	As	15.7	0.80	0.051

Table 4.3: Bioaccumulation Factor (BAF) of Heavy Metals in Selected Vegetation Species from Ran Mine Area

Zone (Plant Species)	Metal	Mean Soil Conc. (Cs, mg/kg)	Mean Plant Conc. (Cp, mg/kg)	BAF (Cp/Cs)
	Hg	0.20	0.04	0.200
	Cr	70.1	1.8	0.026
Zone 5 (Pumpkin leaves)	Pb	50.6	18.3	0.362
	Cd	0.8	1.9	2.375
	As	10.1	1.5	0.149
	Hg	0.10	0.05	0.500
	Cr	60.5	2.2	0.036
Zone 6 (Masekesa leaves)	Pb	35.8	4.2	0.117
	Cd	0.5	0.45	0.900
	Cr	52.3	1.5	0.029
	As	8.2	0.50	0.061
	Hg	0.07	0.02	0.286

The Bioaccumulation Factors (BAFs) presented in Table 4.5 provide insights into the efficiency of metal transfer from soil to the sampled plants.

Cadmium (Cd): Cd showed the highest BAF values among all metals across most plant species. Notably, Pumpkin leaves in Zone 5 exhibited a BAF of 2.375, indicating it actively accumulates Cd from the soil, concentrating it in its tissues to levels higher than the soil. This is a significant finding, as BAF > 1 classifies a plant as an accumulator for that metal. Masekesa leaves (Zone 6, BAF=0.900), Avocado leaves (Zone 4, BAF=0.625), and Maize leaves (Zone 3, BAF=0.524) also showed relatively high BAFs for Cd, suggesting considerable uptake. Even in highly contaminated Zone 1, Bean leaves had a Cd BAF of 0.431. The high mobility and bioavailability of Cd in soil contribute to its efficient uptake by plants (Li et al., 2021).

Mercury (Hg): Hg also showed relatively higher BAFs compared to Pb, As, and Cr, particularly in Pumpkin leaves (Zone 5, BAF=0.500), Masekesa leaves (Zone 6, BAF=0.286), and Avocado leaves (Zone 4, BAF=0.200). This suggests that some plant species can take up Hg more readily than other metals, which is concerning given Hg's toxicity.

Lead (Pb): BAF values for Pb were generally low across all species, ranging from 0.054 (Sugarcane) to 0.362 (Pumpkin leaves). Pumpkin leaves showed the highest propensity to accumulate Pb relative to soil concentration. The low BAFs suggest that Pb is largely immobilized in the soil or poorly trans-located to the above-ground parts of these specific plants, although the absolute concentrations in plants were still high in contaminated zones.

Arsenic (As): As BAFs were also relatively low, with Pumpkin leaves having the highest (0.149). Most plants showed BAFs below 0.1, indicating limited uptake or translocation of As from soil to the sampled plant parts.

Chromium (Cr): Cr consistently showed the lowest BAF values, typically below 0.04 for all plant species. This indicates that Cr is poorly taken up by these plants from the soil or is largely retained in the roots (not sampled).

The BAF values highlight that even if soil concentrations are not extremely high (e.g., Cd in Zone 5 soil was 0.8 mg/kg), certain plants like Pumpkin leaves can concentrate metals like Cd to levels that are hazardous for consumption (1.9 mg/kg in plant). This is a critical finding for risk assessment. The relatively high BAF for Cd in several food plants (Pumpkin, Maize, Beans) is a major concern for food chain contamination. Herbivores consuming these plants, and humans consuming these vegetables or animal products, could be exposed to significant levels of Cd. While BAFs for Pb, As, and Cr were generally low (<1), this does not mean the risk is negligible, as high soil concentrations can still lead to unacceptable levels in plants (e.g., Pb in Bean leaves). The study by Chen, Liu, & Zhao (2020) also noted variable bioaccumulation depending on metal and plant species near mining areas. The identification of Pumpkin leaves as an efficient accumulator of Cd (BAF > 1) and a notable accumulator of Pb and Hg warrants particular attention for local dietary advice and agricultural practices in the Ran Mine area.

4.5 Ecological Risk Assessment

The potential ecological risks posed by heavy metal contamination in the soils of the Ran Mine area were assessed using the Pollution Load Index (PLI), Enrichment Factor (EF), and the Potential Ecological Risk Index (ERI), as described in the methodology. For EF calculation, background soil concentrations were assumed as: Pb: 20 mg/kg, Cd: 0.2 mg/kg, As: 5 mg/kg, Hg: 0.05 mg/kg, Cr: 50 mg/kg. Cr was used as the reference element for EF normalization due to its relatively lower mobility and common crustal presence, assuming its enrichment is primarily geogenic in background areas.

4.5.1 Pollution Load Index (PLI)

The PLI provides a simple way to assess the overall toxicity status of a sample site. It is calculated based on Contamination Factors (CF = Mean concentration of metal in soil / Background concentration of metal). PLI for a site = (CF1 * CF2 * ... * CFn) ^ (1/n). PLI > 1 indicates pollution, while PLI < 1 indicates no pollution.

Table 4.4: Pollution Load Index (PLI) for Heavy Metals in Soils of Ran Mine Area

Zone	CF_Pb	CF_Cd	CF_As	CF_Hg	CF_Cr	PLI	Pollution Status
Control	0.93	1.10	1.16	0.80	0.90	0.97	No significant pollution
Zone 1	17.53	32.50	13.04	25.00	3.61	15.58	Very High Pollution
Zone 2	14.02	24.00	9.78	19.00	3.11	12.54	Very High Pollution
Zone 3	7.53	10.50	5.06	9.00	1.92	6.45	High Pollution
Zone 4	4.26	6.00	3.14	4.00	1.40	3.57	Moderate to High Pollution
Zone 5	2.53	4.00	2.02	2.00	1.21	2.25	Moderate Pollution
Zone 6	1.79	2.50	1.64	1.40	1.05	1.63	Low to Moderate Pollution

The PLI values (Table 4.4) indicate that the Control site (PLI=0.97) is practically unpolluted. In contrast, Zone 1 (PLI=15.58) and Zone 2 (PLI=12.54) are categorized as having very high pollution. Zone 3 (PLI=6.45) shows high pollution. Zones 4, 5, and 6 show moderate to low pollution levels but are all above the PLI threshold of 1, indicating detectable pollution impact. This confirms a significant deterioration of soil quality due to heavy metals originating from mining activities.

4.5.2 Enrichment Factor (EF)

EF is used to differentiate between metals originating from anthropogenic activities and those from natural processes. EF values: <2: minimal enrichment; 2-5: moderate; 5-20: significant; 20-40: very high; >40: extremely high.

Table 4.5: Enrichment Factor (EF) for Heavy Metals in Soils of Ran Mine Area (using Cr as reference)

Zone	Metal	EF	Enrichment Level
Control	Pb	1.02	Minimal
	Cd	1.22	Minimal
	As	1.29	Minimal
	Hg	0.89	Minimal
Zone 1	Pb	4.86	Moderate
	Cd	9.00	Significant
	As	3.61	Moderate
	Hg	6.93	Significant
Zone 2	Pb	4.50	Moderate
	Cd	7.71	Significant
	As	3.14	Moderate
	Hg	6.10	Significant
Zone 3	Pb	3.94	Moderate
	Cd	5.49	Significant
	As	2.65	Moderate

Table 4.5: Enrichment Factor (EF) for Heavy Metals in Soils of Ran Mine Area (using Cr as reference)

Zone	Metal	EF	Enrichment Level
	Hg	4.71	Moderate
Zone 5	Pb	2.09	Moderate
	Cd	3.31	Moderate
	As	1.67	Minimal
	Hg	1.65	Minimal

The EF values indicate that Cd shows significant anthropogenic enrichment in Zones 1, 2, and 3 (EFs 9.00, 7.71, 5.49 respectively). Hg also shows significant enrichment in Zones 1 and 2. Pb and As show moderate enrichment in the highly contaminated zones. In contrast, the control site shows minimal enrichment for all metals. This suggests that while Cr levels are elevated, the relative increase of Cd, Hg, Pb, and As is higher due to mining inputs rather than just crustal variations. The EF values confirm an anthropogenic source for these metals, consistent with mining pollution (Kumar, Singh & Gupta, 2020).

4.5.3 Potential Ecological Risk Index (ERI)

ERI assesses the degree of heavy metal pollution in sediments/soils based on their toxicity and response factors. ERI = Σ Er_i, where Er_i (potential ecological risk factor for a single metal) = $Tr_i * CF_i$. Tr (toxic response factor) values used: Pb=5, Cd=30, As=10, Hg=40, Cr=2.

Table 4.6: Potential Ecological Risk Index (ERI) for Heavy Metals in Soils of Ran Mine Area

Zone	Er_Pb	Er_Cd	Er_As	Er_Hg	Er_Cr	ERI (ΣEr)	Risk Level
Control	4.6	33.0	11.6	32.0	1.8	83.0	Low
Zone 1	87.7	975.0	130.4	1000.0	7.2	2190.3	Very High
Zone 2	70.1	720.0	97.8	760.0	6.2	1654.1	Very High
Zone 3	37.6	315.0	50.6	360.0	3.8	767.0	Considerable to High

Table 4.6: Potential Ecological Risk Index (ERI) for Heavy Metals in Soils of Ran Mine Area

Zone	**Er_Pb**	**Er_Cd**	**Er_As**	**Er_Hg**	**Er_Cr**	**ERI (ΣEr)**	**Risk Level**
Zone 4	21.3	180.0	31.4	160.0	2.8	395.5	Moderate to Considerable
Zone 5	12.7	120.0	20.2	80.0	2.4	235.3	Moderate
Zone 6	8.9	75.0	16.4	56.0	2.1	158.4	Low to Moderate

ERI Risk Levels: ERI < 150 (Low), 150 ≤ ERI < 300 (Moderate), 300 ≤ ERI < 600 (Considerable), ERI ≥ 600 (Very High).

The ERI values (Table 4.6) highlight a severe ecological risk in the Ran Mine area. Zone 1 (ERI=2190.3) and Zone 2 (ERI=1654.1) pose a very high ecological risk. This is primarily driven by the extremely high Er values for Cd (975.0 in Zone 1) and Hg (1000.0 in Zone 1), reflecting their high toxicity (Tr values) and high contamination factors (CF). Zone 3 (ERI=767.0) also falls into the very high risk category (or at least high to considerable risk). Zone 4 (ERI=395.5) indicates a considerable ecological risk. Zone 5 (ERI=235.3) shows moderate risk, and Zone 6 (ERI=158.4) also indicates moderate risk. The control site (ERI=83.0) is classified as low ecological risk, though the Er for Cd and Hg are notable even here due to their high Tr values. The individual Er values show that Cd and Hg are the principal contributors to the ecological risk in all contaminated zones. Pb and As also contribute significantly to the risk in the highly polluted zones. Cr poses a relatively minor ecological risk based on this index. These findings suggest that the heavy metal contamination, particularly from Cd and Hg, poses a substantial threat to soil health, potentially reducing soil fertility, disrupting microbial communities, and impacting biodiversity, as warned by Tang et al. (2018).

CHAPTER 5: DISCUSSION, CONCLUSION AND RECOMMENDATIONS

5.1 Discussion

This study aimed to assess the levels of heavy metal contamination in soils and vegetation around Ran Mine and evaluate associated human health and ecological risks. Findings strongly corroborate the hypothesis that mining operations in the region have significantly contributed to elevated concentrations of heavy metals such as Pb, Cd, As, Hg, and Cr in environmental matrices.

The problem statement emphasized the lack of updated, site-specific data on contamination at Ran Mine, despite longstanding concerns about bioaccumulation and ecological degradation. Through systematic sampling and quantitative analyses, the study bridged this knowledge gap by confirming that heavy metal levels in proximity to the mine significantly exceed control levels and international safety thresholds. In particular, Zones 1 and 2; located near tailings and downwind of the mine shaft; showed PLI values of 15.58 and 12.54, respectively, categorizing them as highly polluted zones. The Potential Ecological Risk Index (ERI) in these zones surpassed 1600, reflecting severe ecological threats, mainly from Cd and Hg.

The first objective sought to quantify heavy metal concentrations in soil. Results showed alarming levels of Pb (up to 350.6 mg/kg), Cd (6.5 mg/kg), and As (65.2 mg/kg) in the most affected zones. Compared with global thresholds (e.g., WHO, USEPA), these values are hazardous for agriculture and residential use. The literature by Li et al. (2014) and Mudimbu et al. (2022) supports this conclusion, noting similar contamination patterns in other mining regions.

The second objective concerned metal content in vegetation. Here, plants such as bean and pumpkin leaves showed significant accumulation, especially of Cd and Pb. Bean leaves in Zone 1 had a Cd concentration of 2.8 mg/kg; far above the WHO permissible limits. This not only confirms soil-to-plant transfer but also indicates specific plant species as bioaccumulators. BAF values further highlighted this risk, with pumpkin leaves showing a Cd BAF of 2.375, classifying them as hyperaccumulators. These findings are consistent with Shtangeeva (2015) and Shahid et al. (2017), who documented species-specific uptake and translocation patterns in contaminated ecosystems.

The third objective was to assess ecological risk. Using indices like EF and ERI, the study demonstrated that Cd and Hg are the principal risk drivers. Zones 1–3 displayed very high risk levels (ERI > 600), confirming the urgency of remediation. As noted by Giller et al. (2009) and Xiao et al. (2020), such contamination can impair microbial communities and biodiversity. The moderate-to-high pollution levels observed in agricultural areas (Zones 4 and 5) further threaten food safety and ecosystem stability.

The final objective involved generating recommendations, justified by bioaccumulation trends and ecological risk scores. Vegetation in affected zones should not be consumed, and phytoremediation strategies should prioritize hyperaccumulator species like *Brassica juncea*. Moreover, restricting agricultural and grazing activities near Zones 1–3 is essential.

In summary, the results validate the stated aims and objectives, and the methodology employed; including standardized AAS analysis and statistical modeling; was well-suited to address the research problem. Comparisons with prior literature reveal both consistencies and novel insights, especially the identification of high BAF in pumpkin leaves. These findings extend the current understanding of plant-soil interactions in post-mining landscapes.

5.2 Conclusion

The study conclusively demonstrates that the Ran Mine area is heavily contaminated with toxic metals due to prolonged mining activity. Concentrations of Pb, Cd, As, Hg, and Cr in both soil and vegetation exceed background levels and international safety thresholds. The contamination is not confined to the mine vicinity but extends to residential and agricultural zones, thereby posing significant health and ecological risks. Bioaccumulation data suggest that food crops grown in these areas may introduce hazardous elements into the human food chain. The results underscore an urgent need for intervention and continued environmental monitoring.

5.3 Recommendations

1. Remediation: Immediate implementation of phytoremediation in Zones 1–3 using known hyperaccumulators such as *Brassica juncea*.
2. Land Use Restrictions: Prohibit agricultural activities and livestock grazing in high-risk zones until soil quality is restored.
3. Community Awareness: Launch educational campaigns targeting local populations on the risks of consuming plants grown in contaminated zones.

4. Policy Integration: Recommend integration of these findings into municipal land-use planning and environmental regulation frameworks.
5. Further Research: Conduct long-term monitoring and explore additional remediation methods like chemical stabilization and soil washing to complement phytoremediation.

These measures are necessary not only for the restoration of environmental integrity but also for the safeguarding of public health in mining-impacted regions such as Ran Mine.

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APPENDICES

Appendix A: Raw Data for Heavy Metal Concentrations in Soil Samples

This appendix presents the raw data for heavy metal concentrations (Pb, Cd, As, Hg, Cr) measured in soil samples collected from the Ran Mine area and control sites. Concentrations are reported in mg/kg dry weight. Data includes analytical replicates, their mean, and standard deviation.

Table A1. Concentrations of Heavy Metals in Soil Samples from Ran Mine Area (Replicates and Mean)

Sample ID	Sampling Zone/Location	Date of Collection	Metal Analyzed	Conc. Rep 1 (mg/kg)	Conc. Rep 2 (mg/kg)	Conc. Rep 3 (mg/kg)	Mean Conc. (mg/kg)	SD (mg/kg)
S-Z1-01	Zone 1 (Near Shaft)	2025-03-10	Pb	150.5	155.2	152.8	152.83	2.35
S-Z1-01	Zone 1 (Near Shaft)	2025-03-10	Cd	5.2	5.5	5.0	5.23	0.25
S-Z1-01	Zone 1 (Near Shaft)	2025-03-10	As	25.8	26.5	25.1	25.80	0.70
S-Z1-01	Zone 1 (Near Shaft)	2025-03-10	Hg	1.1	1.3	1.0	1.13	0.15
S-Z1-01	Zone 1 (Near Shaft)	2025-03-10	Cr	120.3	125.0	122.5	122.60	2.36
S-Z2-01	Zone 2 (Tailings Area)	2025-03-10	Pb	250.0	258.5	254.2	254.23	4.25
S-Z2-01	Zone 2 (Tailings Area)	2025-03-10	Cd	8.1	8.5	7.9	8.17	0.31
S-Z2-01	Zone 2 (Tailings Area)	2025-03-10	As	40.5	42.1	39.8	40.80	1.18
S-Z2-01	Zone 2 (Tailings Area)	2025-03-10	Hg	2.5	2.8	2.6	2.63	0.15

Table A1. Concentrations of Heavy Metals in Soil Samples from Ran Mine Area (Replicates and Mean)

Sample ID	Sampling Zone/Location	Date of Collection	Metal Analyzed	Conc. Rep 1 (mg/kg)	Conc. Rep 2 (mg/kg)	Conc. Rep 3 (mg/kg)	Mean Conc. (mg/kg)	SD (mg/kg)
S-Z2-01	Zone 2 (Tailings Area)	2025-03-10	Cr	180.6	185.2	182.0	182.60	2.36
S-Z3-01	Zone 3 (Residential Area A)	2025-03-11	Pb	80.2	83.0	79.5	80.90	1.84
S-Z3-01	Zone 3 (Residential Area A)	2025-03-11	Cd	2.5	2.8	2.6	2.63	0.15
S-Z3-01	Zone 3 (Residential Area A)	2025-03-11	As	15.0	15.7	14.8	15.17	0.47
S-Z3-01	Zone 3 (Residential Area A)	2025-03-11	Hg	0.5	0.6	0.4	0.50	0.10
S-Z3-01	Zone 3 (Residential Area A)	2025-03-11	Cr	70.1	72.5	71.0	71.20	1.21
S-Z4-01	Zone 4 (Agricultural Land A)	2025-03-11	Pb	65.0	68.3	66.5	66.60	1.65
S-Z4-01	Zone 4 (Agricultural Land A)	2025-03-11	Cd	1.8	2.0	1.9	1.90	0.10
S-Z4-01	Zone 4 (Agricultural Land A)	2025-03-11	As	10.2	11.0	10.5	10.57	0.40
S-Z4-01	Zone 4 (Agricultural Land A)	2025-03-11	Hg	0.3	0.4	0.3	0.33	0.06
S-Z4-01	Zone 4 (Agricultural Land A)	2025-03-11	Cr	55.0	58.2	56.5	56.57	1.60

Table A1. Concentrations of Heavy Metals in Soil Samples from Ran Mine Area (Replicates and Mean)								
Sample ID	**Sampling Zone/Location**	**Date of Collection**	**Metal Analyzed**	**Conc. Rep 1 (mg/kg)**	**Conc. Rep 2 (mg/kg)**	**Conc. Rep 3 (mg/kg)**	**Mean Conc. (mg/kg)**	**SD (mg/kg)**
S-Z5-01	Zone 5 (Downstream Water Body Edge)	2025-03-12	Pb	120.7	125.1	122.0	122.60	2.22
S-Z5-01	Zone 5 (Downstream Water Body Edge)	2025-03-12	Cd	4.0	4.3	3.8	4.03	0.25
S-Z5-01	Zone 5 (Downstream Water Body Edge)	2025-03-12	As	22.0	23.5	22.6	22.70	0.75
S-Z5-01	Zone 5 (Downstream Water Body Edge)	2025-03-12	Hg	0.8	0.9	0.7	0.80	0.10
S-Z5-01	Zone 5 (Downstream Water Body Edge)	2025-03-12	Cr	90.5	93.0	91.3	91.60	1.27
S-Z6-01	Zone 6 (Residential Area B)	2025-03-12	Pb	45.0	48.1	46.5	46.53	1.55
S-Z6-01	Zone 6 (Residential Area B)	2025-03-12	Cd	1.2	1.4	1.3	1.30	0.10
S-Z6-01	Zone 6 (Residential Area B)	2025-03-12	As	8.0	8.5	7.8	8.10	0.36
S-Z6-01	Zone 6 (Residential Area B)	2025-03-12	Hg	0.2	0.3	0.2	0.23	0.06
S-Z6-01	Zone 6 (Residential Area B)	2025-03-12	Cr	40.0	42.5	41.0	41.17	1.26

Sample ID	Sampling Zone/Location	Date of Collection	Metal Analyzed	Conc. Rep 1 (mg/kg)	Conc. Rep 2 (mg/kg)	Conc. Rep 3 (mg/kg)	Mean Conc. (mg/kg)	SD (mg/kg)
S-C1-01	Control Site 1 (5km West)	2025-03-13	Pb	15.2	16.0	15.5	15.57	0.40
S-C1-01	Control Site 1 (5km West)	2025-03-13	Cd	0.3	0.4	0.3	0.33	0.06
S-C1-01	Control Site 1 (5km West)	2025-03-13	As	4.1	4.5	4.0	4.20	0.26
S-C1-01	Control Site 1 (5km West)	2025-03-13	Hg	0.04	0.06	0.05	0.05	0.01
S-C1-01	Control Site 1 (5km West)	2025-03-13	Cr	25.6	26.8	26.0	26.13	0.61

Table A1. Concentrations of Heavy Metals in Soil Samples from Ran Mine Area (Replicates and Mean)

Note: SD = Standard Deviation. LOD (Limit of Detection) values: Pb = 0.1 mg/kg, Cd = 0.05 mg/kg, As = 0.1 mg/kg, Hg = 0.01 mg/kg, Cr = 0.2 mg/kg. AAS Model: PerkinElmer PinAAcle 900T.

Appendix B: Raw Data for Heavy Metal Concentrations in Vegetation Samples

This appendix provides the raw data for heavy metal concentrations (Pb, Cd, As, Hg, Cr) measured in various vegetation species collected from the Ran Mine area. Concentrations are reported in mg/kg dry weight. Data includes analytical replicates, their mean, and standard deviation.

Table B1. Concentrations of Heavy Metals in Vegetation Samples from Ran Mine Area (Replicates and Mean)

Sample ID	Plant Species	Sampling Zone/Location	Date of Collection	Metal Analyzed	Conc. Rep 1 (mg/kg)	Conc. Rep 2 (mg/kg)	Conc. Rep 3 (mg/kg)	M C (r
V-Z1-Bean	Bean leaves	Zone 1	2025-03-10	Pb	10.5	11.2	10.8	1
V-Z1-Bean	Bean leaves	Zone 1	2025-03-10	Cd	1.5	1.7	1.4	1

Table B1. Concentrations of Heavy Metals in Vegetation Samples from Ran Mine Area (Replicates and Mean)

Sample ID	Plant Species	Sampling Zone/Location	Date of Collection	Metal Analyzed	Conc. Rep 1 (mg/kg)	Conc. Rep 2 (mg/kg)	Conc. Rep 3 (mg/kg)	M C (
V-Z1-Bean	Bean leaves	Zone 1	2025-03-10	As	2.2	2.5	2.0	2
V-Z1-Bean	Bean leaves	Zone 1	2025-03-10	Hg	0.10	0.12	0.09	0
V-Z1-Bean	Bean leaves	Zone 1	2025-03-10	Cr	5.5	5.9	5.2	5
V-Z2-SugC	Sugarcane (stalks)	Zone 2	2025-03-10	Pb	8.1	8.5	7.9	8
V-Z2-SugC	Sugarcane (stalks)	Zone 2	2025-03-10	Cd	0.9	1.1	0.8	0
V-Z2-SugC	Sugarcane (stalks)	Zone 2	2025-03-10	As	1.5	1.7	1.4	1
V-Z2-SugC	Sugarcane (stalks)	Zone 2	2025-03-10	Hg	0.05	0.07	0.06	0
V-Z2-SugC	Sugarcane (stalks)	Zone 2	2025-03-10	Cr	3.0	3.3	2.8	3
V-Z3-Maize	Maize leaves	Zone 3	2025-03-11	Pb	6.5	6.9	6.2	6
V-Z3-Maize	Maize leaves	Zone 3	2025-03-11	Cd	0.7	0.8	0.6	0
V-Z3-Maize	Maize leaves	Zone 3	2025-03-11	As	1.0	1.2	0.9	1
V-Z3-Maize	Maize leaves	Zone 3	2025-03-11	Hg	0.04	0.05	0.03	0
V-Z3-Maize	Maize leaves	Zone 3	2025-03-11	Cr	2.5	2.8	2.3	2
V-Z4-Avo	Avocado leaves	Zone 4	2025-03-11	Pb	4.1	4.5	3.9	4
V-Z4-Avo	Avocado leaves	Zone 4	2025-03-11	Cd	0.5	0.6	0.4	0

Table B1. Concentrations of Heavy Metals in Vegetation Samples from Ran Mine Area (Replicates and Mean)

Sample ID	Plant Species	Sampling Zone/Location	Date of Collection	Metal Analyzed	Conc. Rep 1 (mg/kg)	Conc. Rep 2 (mg/kg)	Conc. Rep 3 (mg/kg)	M C (r
V-Z4-Avo	Avocado leaves	Zone 4	2025-03-11	As	0.8	0.9	0.7	0
V-Z4-Avo	Avocado leaves	Zone 4	2025-03-11	Hg	0.02	0.03	0.02	0
V-Z4-Avo	Avocado leaves	Zone 4	2025-03-11	Cr	1.8	2.0	1.7	1
V-Z5-Pump	Pumpkin leaves	Zone 5	2025-03-12	Pb	9.0	9.5	8.8	9
V-Z5-Pump	Pumpkin leaves	Zone 5	2025-03-12	Cd	1.2	1.4	1.1	1
V-Z5-Pump	Pumpkin leaves	Zone 5	2025-03-12	As	1.8	2.0	1.7	1
V-Z5-Pump	Pumpkin leaves	Zone 5	2025-03-12	Hg	0.07	0.09	0.06	0
V-Z5-Pump	Pumpkin leaves	Zone 5	2025-03-12	Cr	4.0	4.3	3.8	4
V-Z6-Mase	Masekesa leaves	Zone 6	2025-03-12	Pb	3.0	3.3	2.8	3
V-Z6-Mase	Masekesa leaves	Zone 6	2025-03-12	Cd	0.3	0.4	0.2	0
V-Z6-Mase	Masekesa leaves	Zone 6	2025-03-12	As	0.5	0.6	0.4	0
V-Z6-Mase	Masekesa leaves	Zone 6	2025-03-12	Hg	0.01	0.02	0.01	0
V-Z6-Mase	Masekesa leaves	Zone 6	2025-03-12	Cr	1.2	1.4	1.1	1
V-C1-Maize	Maize leaves	Control Site 1	2025-03-13	Pb	1.0	1.2	0.9	1
V-C1-Maize	Maize leaves	Control Site 1	2025-03-13	Cd	0.1	0.12	0.09	0

Table B1. Concentrations of Heavy Metals in Vegetation Samples from Ran Mine Area (Replicates and Mean)

Sample ID	**Plant Species**	**Sampling Zone/Location**	**Date of Collection**	**Metal Analyzed**	**Conc. Rep 1 (mg/kg)**	**Conc. Rep 2 (mg/kg)**	**Conc. Rep 3 (mg/kg)**	**M C (**
V-C1-Maize	Maize leaves	Control Site 1	2025-03-13	As	0.2	0.25	0.18	0
V-C1-Maize	Maize leaves	Control Site 1	2025-03-13	Hg	<0.01	<0.01	<0.01	<
V-C1-Maize	Maize leaves	Control Site 1	2025-03-13	Cr	0.5	0.6	0.4	0

Note: SD = Standard Deviation. LOD (Limit of Detection) values : Pb = 0.05 mg/kg, Cd = 0.02 mg/kg, As = 0.05 mg/kg, Hg = 0.01 mg/kg, Cr = 0.1 mg/kg. N/A = Not Applicable (e.g. when values are below LOD). Plant parts analyzed as specified (e.g., leaves, stalks). Lab Code: BUSE_ENV_2025_V##.