BINDURA UNIVERSITY OF SCIENCE EDUCATION

DEPARTMENT OF ENVIRONMENTAL SCIENCE

Accumulation of trace elements in coal ash-amended agricultural soil

By

Chakanyuka Millicent (B212528B)

A Research project submitted in partial fulfilment of the requirements of the Bachelor of Science Honors degree in Safety, Health and Environmental Management

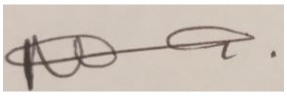
MAY 2025

DECLARATION

To be completed by the student

Registration number B212528B

I, Millicent Chakanyuka, do hereby declare that this is entirely the product of my research carried out with the partial fulfilment of the requirements of a Bachelor of Science Honors Degree in Safety, Health and Environmental Management. It was never used on any other academic work, and all references to previously done work have been clearly shown.

Student signature  Date 28 May 2025

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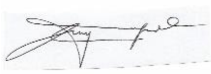
Department Chairperson  Date 30 May 2025

DEDICATION

The research is dedicated to the Chakanyuka family for their warm support, encouragement and love.

ACKNOWLEDGEMENT

First and foremost, thanks are given to God Almighty for granting me life and strength to sail through even in difficult times during my research. In addition, I would like to thank my guardians for the support to study occupational health and safety and the unwavering care and support they showed me throughout this whole journey. My utmost gratitude to my dissertation supervisor, Dr. A. Kanda, who was patient throughout this whole journey and for his intellectual support and guidance. I would also want to appreciate Mr. Richakara, the laboratory technician who helped me during experiments and my colleagues, S. Bettar and B. Murandu, for the academic, emotional and social support they rendered.

ABSTRACT

Background: The addition of coal ash to agricultural soil can improve soil properties and nutrient availability, but may also introduce toxic trace elements. Coal ash is increasingly considered a viable soil amendment due to its mineral content and potential to enhance soil structure and nutrient levels. However, its use may also introduce harmful trace elements into agricultural systems, raising concerns about long-term environmental and health impacts.

Objective: The long-term accumulation of coal ash in agricultural soil was evaluated for trace element loading. This study aimed to evaluate the long-term accumulation of trace elements in agricultural soil resulting from coal ash application. The focus was on assessing how repeated amendments influence trace element concentrations and potential risks.

Methods: An experimental design was implemented in agricultural plots where soil was amended with coal ash over an extended period. Soil samples were systematically collected and analysed for key trace elements. Soil physicochemical properties were also measured to understand changes in fertility and structure.

Key findings: Coal ash amendment reduced soil pH, shifting conditions toward slightly acidic conditions from 7.049 to 6.124. Statistical analysis revealed no significant differences between treatments (p-values 0.474-0.854), indicating that coal ash amendment did not produce statistically detectable changes in soil heavy metal concentrations.

Conclusion: Coal-ash addition introduced only trace-level amounts of Cd, Cu, Cr, Ni, Pb and Zn to the soil, while Ni and Pb rose modestly, yet every metal remained well below international guideline limits. Statistical tests ($p > 0.05$) confirmed no significant elevation above background. Consequently, the amended soil is classified as "uncontaminated to very slightly contaminated," demonstrating that the coal ash used is chemically benign for agronomic use under the conditions tested.

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CHAPTER 1: INTRODUCTION

1 Introduction

1.1 Background of the study

Coal remains a dominant energy source globally, particularly in developing countries where it provides a reliable and affordable option for electricity generation (Clark, 2020). In Zimbabwe, Hwange Thermal Power Station is the largest coal-fired power plant, generating large volumes of coal ash as a by-product. Coal ash contains essential nutrients beneficial to soil fertility and trace elements that can be harmful when they accumulate in the soil (Abdullahi et al., 2021).

In recent years, there has been a growing trend of repurposing coal ash in agriculture due to its liming properties and potential to enhance soil structure(Naskar & Sharma, 2024). Despite these perceived benefits, concerns about the potential ecological and human health implications have emerged. Studies have shown that repeated application of coal ash may lead to toxic build-up of trace elements in the soil, affecting plant growth and entering the food chain(Evans et al., 2023). This has been reported in South Africa and India, where food crops grown on coal ash-amended soils contained trace element levels exceeding safety thresholds.

Despite these global insights, limited studies have been conducted in Zimbabwe to understand the implications of coal ash reuse in agriculture, particularly in the Hwange district. Hwange is uniquely positioned due to its proximity to the thermal power operations and its dependence on agriculture, making it a critical area for assessing trace elements accumulation. Understanding the extent of contamination and the associated risks is crucial for guiding sustainable environmental and agricultural policies(Hou et al., 2023).

1.2 Problem statement

Coal ash is used as a nutrient-rich soil supplement, but it contains toxic trace elements that can build up over time(Naskar & Sharma, 2024). These trace elements may leach into groundwater or be absorbed by crops, raising significant food safety issues(Evans et al., 2023). Despite the frequent use of coal ash, little is known about its long-term implications in different environmental settings, especially in Zimbabwe. This study aims to determine the concentrations of selected toxic trace elements in agricultural soils amended with coal ash and to ascertain the degree of agricultural contamination with these elements.

1.3.1 Aims

- To evaluate the accumulation of trace elements in coal ash amended agricultural soil.

1.3.2 Objectives

- To determine the concentration of selected toxic trace elements (Zn, Cd, Ni, Pb, Cr, and Cu) in agricultural soils amended with coal ash.
- to determine the degree of agricultural soil contamination with toxic trace elements in coal ash.

1.4 Significance of the study

This study is significant as it investigates the environmental and health implications of coal ash application in agriculture by quantifying the concentration of trace elements in amended soils and assessing the degree of contamination. The accumulation of these trace metals can pose risks to food safety, soil quality, and groundwater systems. For instance,(Liu et al., 2020) found that hazardous trace elements in coal fly ash, such as Cr and Cu, exhibit varying mobility depending on ash type. Similarly, (Sun et al., 2021) demonstrated that repeated coal ash application led to increased bioavailability of Pb and Zn in Pakchoi crops, raising concerns about long-term soil contamination. These findings underscore the need for careful monitoring and regulation of coal ash use in agriculture.

1.5 Hypothesis

H_0: There is no significant accumulation of trace elements in coal ash amended agricultural soils in Hwange district

H_1: There is a significant accumulation of trace elements in coal ash amended agricultural soils in the Hwange district.

1.6 Assumptions

- The coal ash used for soil amendment contains varying concentrations of trace elements, including potentially toxic ones, along with beneficial nutrients.
- 1content, texture) that influence the mobility and retention of trace elements.
- The assumption holds that microbial activity in the soil will not be significantly altered by coal ash amendments, thereby enabling a consistent analysis of trace element mobility and accumulation

1.7 Limitations

- The inability to track historical rates and the lack of seasonal data
- Financial constraints restricted the number of samples analysed, and the study relied on laboratory facilities with limited advanced detection capabilities.

1.8 Delimitations

- The study is geographically limited to agricultural plots in the Hwange district, within a defined radius from coal ash disposal sites.
- It focuses on trace elements in topsoil samples and excludes water testing due to resource limitations.

CHAPTER 2: REVIEW OF LITERATURE

2 Literature review

2.1 Introduction

This chapter presents an overview of existing knowledge on coal ash composition, its use in agriculture, associated environmental and health risks, and trace element accumulation. It identifies research gaps and establishes a theoretical foundation for the study.

2.2 Composition and use of coal ash in agriculture

Coal ash is a fine particulate residue obtained after coal combustion(Kotelnikova et al., 2022). Coal ah has proven beneficial in enhancing soil structure; its long-term effects are often underestimated. Some studies have shown elevated soil pH and metal concentrations in fields with repeated coal ash amendments(Kotelnikova et al., 2022). These changes can alter microbial activity and nutrient cycling processes, with long-term impacts on ecosystem health. Table 4.1 below shows the composition of coal ash.

Table 2.1 Composition of coal ash

Country (area)	Composition of coal ash (%)	Reference
United States	SiO_2: 40–60, Al_2O_3: 15–30, Fe_2O_3: 5–15, CaO: 1–10, MgO: 0.5–4, Na_2O: 0.1–2, K_2O: 0.5–2	(Hanum, 2023)
China	SiO_2: 40–60, Al_2O_3: 15–35, Fe_2O_3: 4–15, CaO: 1–10, MgO: 0.5–3, Na_2O: 0.1–2, K_2O: 0.5–2	(Zimar, 2022)
India	SiO_2 : 37.78–68.18, Fe_2O_3 : 7.05–28.69, Al_2O_3 : 7.83–33.22, CaO : 0.11–0.96, MgO :0.24–1.27, TiO_2 :0.08–1.91	(Sharma, 2014)
Germany	SiO_2: 40–60, Al_2O_3: 15–30, Fe_2O_3: 5–15, CaO: 5–25, MgO: 0.5–4, Na_2O: 0.1–2, K_2O: 0.5–2	(Hanum et al., 2023)
Australia	SiO_2: 50–70, Al_2O_3: 15–30, Fe_2O_3: 5–15, CaO: 1–10, MgO: 0.5–3, Na_2O: 0.1–2, K_2O: 0.5–2.9	(Zimar, 2022)

2.3 Effects of adding coal ash to soil properties

Table 2.2 shows the effects of adding coal ash on soil physicochemical properties. Literature indicates that:

Soil property	Description of effect	Reference
pH.	Often increases soil pH (alkaline nature of most coal ash)	(Kotelnikova, 2022)

Nutrient content	Adds macronutrients and some micronutrients.	(Kumar & Kumar, 2023)
Physical properties	Improves soil structure (aggregation porosity), increases water-holding capacity, especially in sandy soils and reduces bulk density.	(Belviso, 2022)
Cation Exchange Capacity(CEC)	The variable can increase CEC depending on ash and soil type.	(Palansooriya, 2020)
Trace elements leaching and bioavailability	Coal ash is a direct source of trace elements. Leaching potential is influenced by ash type, application rate, pH, redox conditions, and organic matter.	
Biological properties(microbial activity)	Can have varied effects; potentially stimulating at low rates due to improved conditions, but inhibitory at high trace element concentrations.	(Varshney, 2022)

Table 2.2 Effects of adding coal ash to soil properties

2.4 Effects of adding coal ash to the environment

The addition of coal ash to the environment, particularly in agricultural settings, can have both beneficial and detrimental effects. Coal ash contains essential nutrients which can improve soil structure, pH, increases CEC and fertility when applied in controlled amounts. Studies have shown that coal ash can enhance water retention and reduce soil acidity(Abdullahi et al., 2021; Clark et al., 2020). Moreover, its pozzolanic properties can improve the physical characteristics of soil, promoting better root growth and crop yield under certain conditions.

The addition of coal ash to the environment, particularly when used as a soil amendment, can lead to increased accumulation of trace elements that pose a risk to ecosystems and human health(Kamara et al., 2023). Coal ash contains organic and inorganic pollutants that can leach into surface and ground water, especially when deposited in ponds or unlined landfills, affecting agricultural productivity and food safety due to their persistence, disturbance of microbial communities, and decreased fertility(Kamara et al., 2023). Furthermore, breaches of coal ash impoundments have released millions of tons of coal ash into rivers and farmland, contaminating soils and drinking water supplies for years(Hyeop-Jo et al., 2025)

2.5 Effects of adding coal ash to plants and human health

Coal ash application in agriculture has generated considerable interest due to its dual role as a nutrient source and a potential pollutant. While the material may enrich soil with essential elements like calcium, magnesium, and potassium, studies have raised concerns about the accumulation of trace metals in plant tissues, which may compromise crop safety and soil health (Liu et al., 2020; Sun et al., 2021) demonstrated that the speciation and mobility of hazardous elements in fly ash vary by ash type, influencing leaching behavior and bioavailability. Such contamination not only inhibits plant physiological functions, such as root development and enzymatic activity, but also carries broader implications for human health. Chronic exposure to coal ash through inhalation, ingestion, or groundwater consumption has been associated with respiratory illness, neurotoxicity, and increased cancer risk due to heavy metal toxicity (Hussain et al., 2020). These findings underscore the importance of regulating coal ash use in agroecosystems to mitigate ecological risks while maximising potential soil conditioning benefits.

2.6 Total trace elements concentration Vs. fractions

The total concentration of trace elements in coal ash amended soils refers to the overall quantity of metals present in the soil, regardless of their chemical form or mobility. While the concentration provides a general indication of contamination levels, they do not necessarily reflect the actual environmental risk. Several studies have shown that elevated total concentrations of heavy metals in coal ash amended soils can exceed regulatory thresholds, raising concerns about potential accumulation in crops and leaching into groundwater.

Fractional analysis plays a critical role in determining mobility and bioavailability. It shows that trace elements are not uniformly distributed in soil matrices and exist in the soil in different chemical forms. For example, research found that while the total concentration of Cr and Pb in coal ash amended soils was considerable, a large proportion was bound in the residual fraction. On the other hand, elements like Cd and Zn were more prevalent in the exchangeable and carbonate-bound fractions, posing a higher environmental risk due to their greater solubility and potential uptake by plants(Mguni, 2015).

2.7 Summary

Recent studies of coal ash-amended soils in Hwange District show that total concentrations of trace elements such as Zn, Cd, Ni, Pb, Cr, Cu often exceed global background levels, posing environmental and agricultural risks(Mutyavaviri et al., 2024), and total concentration alone does not adequately reflect mobility and bioavailability; fractional distribution is equally important to understanding risk. Trace elements are not homogeneously distributed in soil matrices; elements such as Cd and Zn tend to be found mostly in exchangeable and carbonate-bound fractions, which are mobile and bioavailable (Li et al., 2024; Mashishi et al., 2024).

CHAPTER 3: METHODS AND MATERIAL

3 Methods and material

3.1 Description of the study area

The study was conducted in Ward 15, in Makwika village in Hwange Fig (3.1). Hwange district lies in the North-Western part of Zimbabwe, and is home to the country's largest coal-fired power station. It is approximately positioned at 18.5^0 S latitude and 26.5^0 E longitude (Fig. 3.1). The region features a mix of flat plains and gently rolling hills, with elevations ranging from 900 to 1200 meters above sea level. The topography significantly influences local hydrology, affecting how water is distributed and stored in the landscape.

The area is semi-arid with sandy soils and smallholder farming activities. Average temperatures range from 20°C to 30°C, with extremes reaching up to 40°C during the hottest months. This variability in temperature and precipitation plays a crucial role in agricultural productivity and the potential for trace element accumulation in soils. Coal ash is readily available due to proximity to the power plant and is often applied by farmers without regulatory oversight (Mutyavaviri et al., 2024).

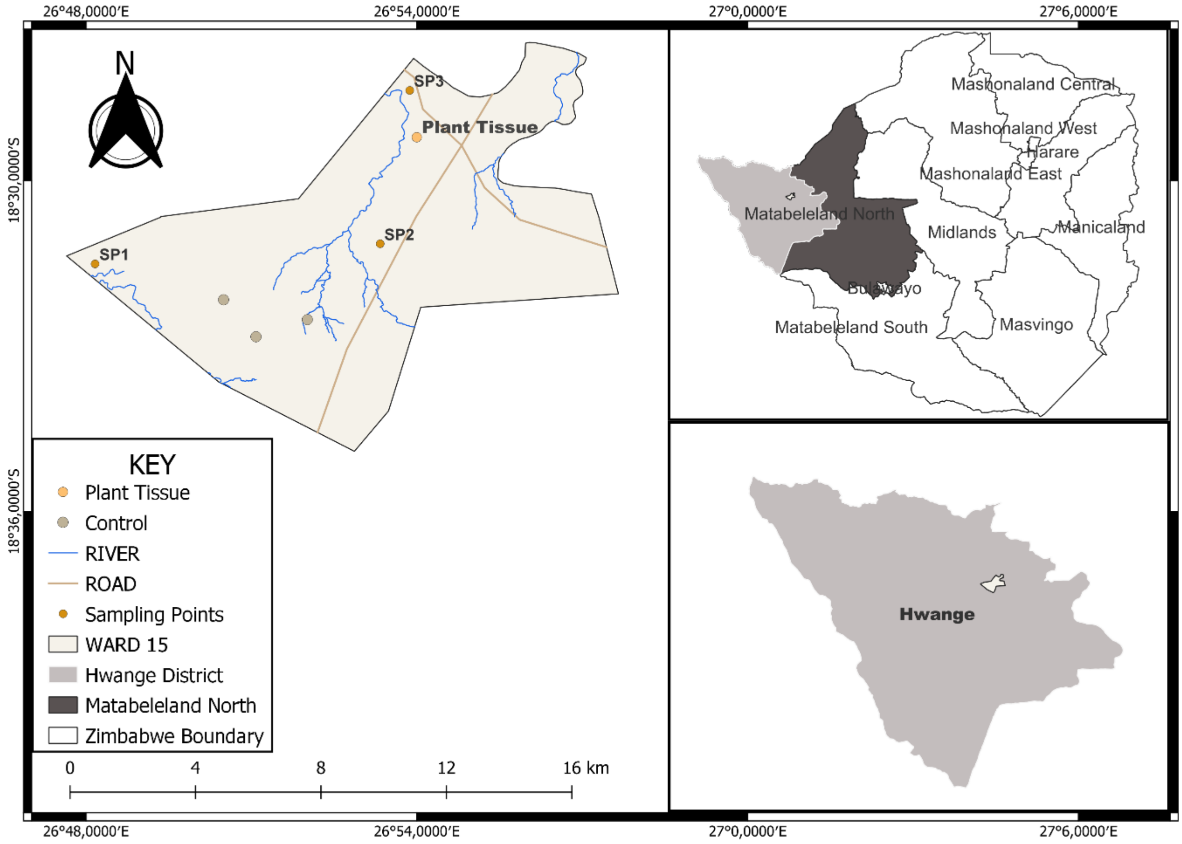


Figure 3.1 Map of Zimbabwe showing the location of Matebeleland North and Ward 15 in Makwika district

3.2 Research design

Experimental design refers to the structured approach used to test hypotheses by comparing outcomes across different treatments. In this study, the design involved comparing coal ash-amended plots (SP1, SP2, SP3) with control plots (C1, C2, C3) to assess trace element accumulation. Each treatment was replicated across three plots to ensure statistical reliability and account for spatial variability. This layout allows for clear differentiation between the effects of coal ash and natural soil conditions. The advantage of this design lies in its ability to isolate treatment impacts while minimising confounding factors. Similar randomised block designs have been used in India and South Africa(Mashishi et al., 2024) to evaluate coal ash effects on soil fertility and crop performance under field conditions(Li et al., 2024).

3.3 Establishment of sampling sites

The target population included six agricultural plots located in Ward 15 within a 15km radius of the coal ash disposal sites. The plots were selected based on uniformity in soil type, cropping history, accessibility, and proximity to coal ash sources. Three plots were designated as experimental sites, where coal ash was deliberately applied, and the other three as controls. The geographic coordinates of each site were recorded using GPS.

Table 3.1 Established experimental and control plots in Ward 15 for sampling (composites for coning and quartering).

Site	Total samples collected	Sub-samples used for the composite
SP1	10	4
SP2	10	4
SP3	10	4
Control 1	10	4
Control 2	10	4
Plant leaves	10	4
Plant roots and stems	10	4

3.4 Data collection

Soil samples of approximately 1 kg were collected at a depth of 0-15 cm using a stainless steel auger. Each sample was labelled, stored in polyethene containers, and made sure contamination was prevented. A systematic zigzag sampling pattern was employed to ensure representative sampling across each selected site. This technique involves collecting soil samples while walking in a zig-zag pattern across the field, which helps capture the spatial variability of trace elements in the soil. Trace element analysis was performed using a FAAS SCITEK model SP-AA3604F; SP-AA3608F that was manufactured in China. The reagents were bought at Zimlabs.

3.5 Data management

3.5.1 Data cleaning and capture

All soil samples were collected using standardised protocols and were labelled. Cleaning included correcting transcription errors and standardising units for example mg/kg.

3.5.2 Determination of the extent of soil pollution with trace elements

3.5.2.1 Geo-accumulation index (I_{geo})

The I_{geo} is a crucial tool for assessing the degree of accumulation of trace elements in coal ash-amended agricultural soil. Originally introduced by Müller in 1969, it has become a standard method for evaluating pollution levels, particularly in contexts involving industrial activities such as coal mining and the use of coal ash as an agricultural soil amendment(Hyeop-Jo et al). It quantifies the level of metal pollution by comparing current concentrations to pre-industrial levels (Rezaei et al., 2020)

The I_{geo} index is calculated using the following formula:

$$Igeo = log2(\frac{Cn}{1.5 \times Bn}) \qquad \text{Equation 1}$$

Where:

- C*n* is the measured concentration of the trace element in the soil sample
- B*n* is the geochemical background concentration of the trace element

- The factor 1.5 is used as a background matrix correction factor to account for possible variations in the background data due to lithogenic effects

3.5.2.2 Enrichment factor (EF)

The enrichment factor (EF) allows the assessment of the degree of anthropogenic activities. EF is based on the standardisation of a tested element against a reference point. The most common reference elements are Sc, Mn, Ti, Al, and Fe, and Fe is used as a reference element in this case. The value of EF was calculated using the modified formula based on the equation suggested by Buat-Menard and Chesselet(Hyeop-Jo et al., 2025):

$$EF = \frac{Cn(sample)/Cref(sample)}{Bn(background)/Bref(background)} \qquad \text{Equation 2}$$

Where:

- C_n(sample) is the content of the examined element in the examined environment
- C_{ref}(sample) is the content of the reference element in the examined environment
- B_n(background) is the content of the examined element in the reference environment
- B_{ref} (background) is the content of the reference element in the reference environment

3.5.2.3 Degree of contamination (Cd)

The contamination degree (C_d) is a cumulative index that provides an overall assessment of the contamination level by multiple trace elements in a sample. It is derived from the sum of individual contamination factors for each element(Hyeop-Jo et al., 2025)

$$Cf = \frac{Cn}{Bn} \qquad \text{Equation 3}$$

Where:

- Cn is the measured concentration of the trace element ‘n’ in the soil sample
- Bn is the geochemical background value of the corresponding trace element ‘n’

Then Cd is calculated as the sum of all individual Cf values

$$Cd = \sum_{i=1}^{n} Cfi \qquad \text{Equation 4}$$

3.5.3 Statistical analysis

In order to meet the study's objectives and test the stated hypotheses, statistical analysis was employed to interpret soil concentrations. The choice of the statistical tool was informed by the nature of the data distribution. Firstly, normality tests were conducted using the Shapiro-Wilk test to assess whether the dataset met parametric assumptions. To compare trace elements concentrations across all sampling sites, descriptive statistics were calculated.

When comparing mean concentrations between experimental and control plots, the study employed an Independent Samples t-test, which was conducted using Microsoft Excel. In all statistical comparisons, a significance threshold was set at the 95% confidence level ($p \leq 0.05$) to determine whether differences were statistically significant.

3.6 Quality assurance

Equipment and tools were thoroughly cleaned before and in between analyses. Standard analytical methods were used, for example, the digestion method adopted from US EPA Method 3050B. The grade of the reagents was ACS grade, AR (Analytical Reagent) grade, and Spectrophotometric grade and they were bought at Zimlabs. The AAS instrument was optimised for use using the manufacturer's manual. Blanks and standards were run first to ensure precision. A total of three standards were used to calibrate the AAS machine and calibration of the machine was done after every 10 runs.

CHAPTER 4: PRESENTATION OF RESULTS

4 Results

4.1 Variation of soil quality parameters

Table 4.1 shows the variation of soil quality parameters with sampling sites. The results of the descriptive statistics indicate that coal ash-amended soil contained elevated levels of trace elements. The control plots were alkaline whilst the experiment was slightly acidic.

Table 4.1 The variation of soil quality parameters. Values are expressed as mean±SE mg/kg.

Soil quality parameter	Coal ash-amended soil			Control		
	SP1	SP2	SP3	C1	C2	C3
pH.		6.106±0.305			7.0245±0.351	7.074±0.354
Cd	0.0053±0.02	0.0006±0.47	0.0018±0..35	0.0006±0.25	0.0013±0.0038	0.0007±0.42
Cr	2.2591±1.95	1.3366±0.95	0.4907±0.60	1.9213±0.14	2.0041±0.56	2.1939±0,96
Cu	1.0450±0.85	0.7172±0.60	0.2780±0.05	0.9181±0.0.07	0.9341±0.0747	0.9686
Fe			12.5543±1.54	13.0698±1.95	13.0894±1.87	13.0959±1.90

Ni	1.8093±0.95	0.9529±0.62	0.2982±0.44	0.4044±0.006	0.4477±0.012	0.4642±0.018
Pb	0.107±0.016	0.0600±0.009	0.0162±0.0024	0.2241±0.044	0.2028±0.035	0.2395±0.05
Zn	0.8565±0.0857	0.8014±0.0801	0.2936±0.0294	1.5030±0.32	1.5070±0.35	1.5852±0.44

Table 4.2 Comparison of soil property parameters in coal ash-amended soil and control soil. Values are expressed as mean±SE mg/kg

Soil quality parameter	Coal ash-amended soil	Control soil	p-value
pH.	6.124±0.45	7.049± 0.53	
Cd	0.002567±0.0013	0.00867±0.0002	0.474
Cr	1.362133±0.51	2.039767±0.081	0.854
Cu	0.683±0.014	0.940267±0.22	0.727

Ni	1.020133±0.43	0.438767±0.015	0.685
Pb	0.61067±0.0262	0.225467±0.0106	0.611
Zn	0.650500±0.027	1.531733±0.18	0.82

The control soil maintained a neutral to slightly alkaline pH and served as the baseline for heavy metal comparisons compared to the experiment as displayed in table 4.2 above. Statistical analysis revealed no significant differences between treatments for any measured parameter (all p-values > 0.05), with p-values ranging from 0.474 to 0.854. This indicates that while numerical differences exist between coal ash-amended and control soils, these variations are not statistically significant at the 95% confidence level.

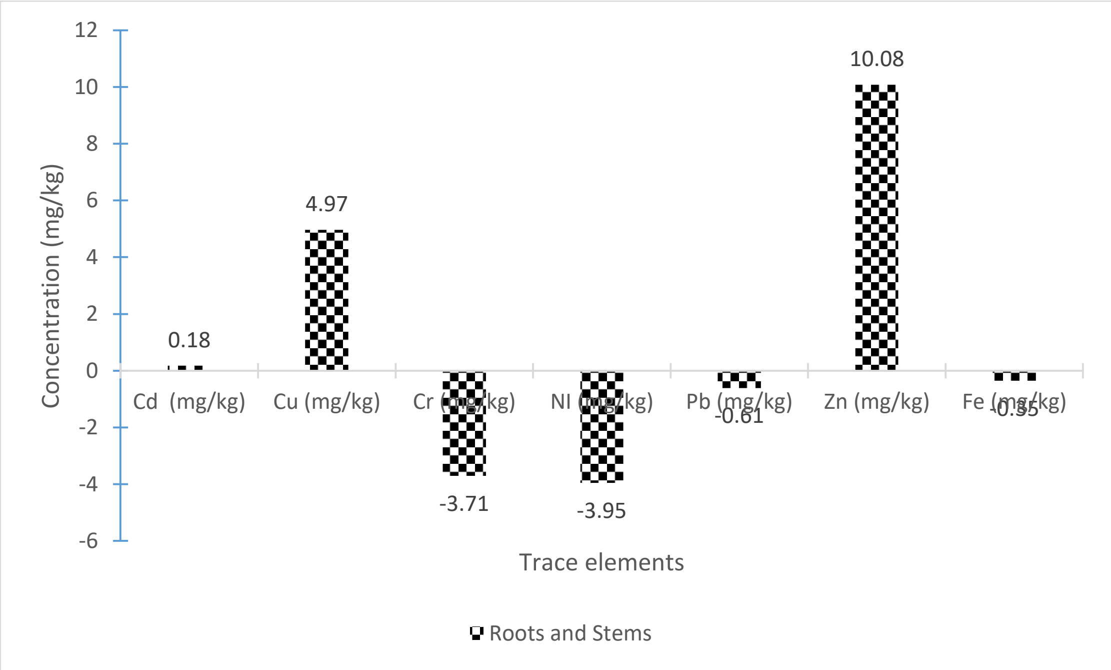
Table 4.3 shows a comparison between measured soil quality characteristics of coal ash-amended soil and FAO soil quality guidelines for agriculture. The results of the t-test between measured soil quality characteristics of coal ash-amended soil and the threshold values indicate that all the concentrations were within the recommended limit.

Table 4.3 Comparison between measured soil quality characteristics of coal ash-amended soil and FAO soil quality guidelines for agriculture. Values are expressed as mg/kg

Soil quality parameter	Coal ash-amended soil	FAO soil quality guideline	p value
pH.	6.106	5.5-7.2	0.75
Cd	-0.000087	1	0.0566
Cr	2.0398	100	0.2601
Cu	0.940267	100	0.3073
Ni	0.438767	50	0.2520
Pb	0.222133	50	0.0047
Zn	1.53173	200	0.0083

4.2 Concentration of trace elements in vegetables growing in ash-amended soil

Fig 4.1 shows the concentration of measured trace elements in plant parts. The results indicate that the varying concentrations of seven selected trace elements (Cd, Cu, Cr, Ni, Pb, Zn, and Fe) in two distinct plant compartments: leaves, and roots and stems. The concentrations are expressed in milligrams per kilogram (mg/kg) on a dry weight basis. The negative indicates concentration below detection limits.



4.3 Extent of trace element pollution of coal ash-amended soil

The extent of soil pollution with trace elements was evaluated with the geo-accumulation index (I-geo), enrichment factor (EF) and the degree of contamination (Cd). SP1 emerges as the most severely contaminated site, constantly ranking highest across all contamination indices, while SP2 had the highest Cd value. Table 4.4 below shows a summary of all the multi-index assessment.

Table 4.4 Extent of soil pollution with trace elements using I-geo, EF and Cd

	Coal ash-amended soil plot					
Index	SP 1		SP 2		SP 3	
	Value	Class	value	Class	Value	class
I-geo	2.02272	Moderately to high contamination	0.76868	Uncontaminated to moderately contaminated	1.78336	Moderately contaminated
EF	4.4740356	Moderate enrichment	2.571428571	Moderate enrichment	1.138220237	Low enrichment
Cd	15.7894	Very high	10.4670	Very high	3.9864	Considerable

CHAPTER 5: DISCUSSION

5 Discussion

5.1 Introduction

This chapter examines the accumulation of trace elements in agricultural soils following amendments with coal ash, offering a critical interpretation of the findings presented earlier. The discussion examines the patterns and concentrations of key trace elements, including arsenic, lead, cadmium, and mercury, and assesses their potential implications for soil health, crop safety, and long-term environmental sustainability. Particular attention is given to the interaction between coal ash composition, soil properties, and elemental mobility, contextualised within the broader framework of agricultural practices in regions utilising coal-derived amendments. By comparing the study's findings to existing literature and anticipated outcomes, this chapter identifies areas of convergence and divergence, highlighting both the potential benefits and environmental risks associated with the use of coal ash.

5.2 Variation of soil quality parameters

The results indicate that coal ash-amended soils generally show elevated concentrations of trace elements compared to control soils. The elevated pH in ash-amended soils (SP1: 7.0245, SP2: 7.074) may reduce metal bioavailability, but does not prevent accumulation. Similar findings were reported in studies from India and China, where coal ash application increased Cr, Ni, and Pb in soils, raising concerns about long-term contamination and crop uptake(Li et al., 2024) (Shukla et al., 2020; Wang et al., 2021). These results support the hypothesis (H_1) of significant trace element accumulation in Hwange district soils and highlight the need for strict regulation of ash application rates.

5.3 Concentration of trace elements in plant tissue

The accumulation of trace elements in plant tissues amended with coal ash reveals distinct patterns between leaves and roots/stems. The data indicate that Zn and Fe are the most concentrated in leaves, suggesting active translocation and uptake, possibly due to their roles in photosynthesis and enzymatic functions(Li et al., 2024). In contrast, Cd and Cu show slightly higher concentrations in roots and stems, consistent with their tendency to bind to root cell walls as a detoxification mechanism.

Notably, negative values for Cr, Ni, Pb, and Fe in roots and stems may reflect analytical variability or metal exclusion mechanisms, as some plants restrict upward mobility of toxic metals to protect aerial tissues(Li et al., 2024). These results underscore the importance of tissue-specific metal partitioning in assessing environmental risk and phytoremediation potential of coal ash-amended soils.

5.4 Extent of soil trace element pollution of coal ash-amended soil

The geo-accumulation index (I-geo) values reveal a gradient of contamination across the amended plots, with SP1 (2.02) classified as “moderately to highly contaminated,” SP3 (1.78) as “moderately contaminated,” and SP2 (0.77) as “uncontaminated to moderately contaminated.” These results indicate that coal ash application markedly affects trace element build-up, especially in SP1, likely due to higher ash application or lower buffering capacity. Similar contamination levels were reported by, who found elevated I-geo values in coal-impacted soils across Eurasia and Africa, highlighting coal ash’s influence on soil geochemistry(Mashishi et al., 2023).

Enrichment factor (EF) analysis further supports anthropogenic influence, with SP1 and SP2 showing moderate enrichment (EF >2), while SP3 exhibits low enrichment (EF ≈1.13). These findings align with Frankel et al. (2025), who observed elevated EF values for Cd, Pb, and Zn near coal ash landfills in Virginia, USA. The EF values in this study indicate that coal ash contributes significantly to trace metal enrichment, particularly in SP1, where Cd levels reached 15.79 mg/kg, classified as “very high.” This mirrors results from (Mashishi et al., 2024), who documented similar Cd concentrations in South African coal discard sites, raising concerns about long-term soil and crop safety.

5.5 Limitations

One key procedural limitation that may affect the interpretation of results is the spatial variability across sample plots since the study relies on a limited number of sampling plots, which could influence trace element distribution and enrichment patterns. Additionally, inconsistencies in coal ash composition and the timing of sample collection—particularly seasonal variations in moisture and temperature—may have impacted trace metal mobility and uptake. The lack of long-term monitoring also limits the ability to assess cumulative effects and temporal trends, potentially underestimating chronic contamination risks.

5.6 Summary

The chapter establishes that coal ash-amended soils in Hwange exhibit elevated levels of trace elements—particularly cadmium—posing risks to soil health, crop safety, and ecological stability. It supports existing literature (2020–2025) that warns of heavy metal contamination from coal ash while adding plot-specific insights using I-geo and EF indices to show spatial variability in pollution levels. By grounding its findings in localised data, the study enhances broader arguments on sustainable waste reuse, providing evidence to strengthen calls for stricter environmental regulation and targeted monitoring in agricultural settings.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The study revealed a clear accumulation of trace elements in coal ash-amended agricultural soils in Hwange, with varying degrees of contamination observed across the plots, notably "Moderately to high contamination" for SP 1. Furthermore, specific elements, particularly Cadmium, exhibited "Very high" contamination factors in plant tissues, indicating significant uptake and potential transfer within the food chain. This study is distinct from earlier works by providing specific, recent empirical data on trace element accumulation from coal ash in the agricultural context of the Hwange district, Zimbabwe, a region experiencing direct coal-related industrial activities.

This research is vital for knowledge by quantifying local contamination levels and offers practitioners crucial data for informed decision-making regarding sustainable agricultural practices and coal ash waste management in the region. Future research should focus on long-term monitoring of these sites, assessing the bioavailability of these accumulated trace elements to a wider range of crops, and evaluating their precise transfer rates into the local human food chain.

6.2 Recommendations

- Apply coal ash in controlled quantities and monitor regularly: Coal ash can improve soil structure and pH, but due to the presence of potentially toxic trace elements (e.g., Cd, Pb, Cr), its application should be limited to recommended rates and supported by regular soil and plant monitoring**.** This helps prevent heavy metal accumulation and groundwater contamination.
- Conduct fractional analysis (speciation) alongside total metal concentration: Total metal concentration alone is insufficient to assess environmental risk. It is

essential to conduct metal fractionation (bioavailability studies) to determine which metals are mobile and likely to be taken up by crops. This allows for better risk assessment and management.

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APPENDIX 1

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