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Health Risk Assessment of Exposure to Heavy Metals in Soils Near Mine Dumps

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UNIVERSITY OF THE WITWATERSRAND



FACULTY OF HEALTH SCIENCES

SCHOOL OF PUBLIC HEALTH

Title: Health Risk Assessment of Exposure to Heavy Metals in Soils Near Mine Dumps

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Research report submitted for the Degree of Master of Public Health in Exposure and Health.

September 2025

Declaration

Under the expert guidance of Dr. Tafadzwa Makonese and Prof. Masilu Daniel Masekameni, I, Badimwena Jacques Tshunza (student number: 2590078), hereby declare that my research project titled "Health Risk Assessment of Exposure to Heavy Metals in Soils Near Mine Dumps" is an original work solely authored by me. This study is being submitted as a partial fulfilment of the requirements for the Master of Public Health degree, specifically focusing on Health and Exposure, at the University of the Witwatersrand School of Public Health in Johannesburg.

This research project has not been presented or submitted for review at any other institution or university. I conducted the entire research process, which included designing the study, meticulously collecting field data, and thoroughly analyzing the results. I utilized Grammarly to correct any grammatical errors in the report.

Key findings and insights from this study are intended to be shared at various academic conferences. They will be submitted for publication in reputable peer-reviewed journals in the field of public health. To ensure the integrity of my work, comprehensive references have been included for each source utilized throughout this investigation. Furthermore, the signed Plagiarism Declaration Form, attached as Appendix A, outlines the Senate's plagiarism policy, affirming my commitment to maintaining academic honesty and integrity in my research endeavours.

Badimwena Jacques Tshunza



14 September 2025

Dedication

I want to convey my profound gratitude to the Lord Almighty for His steadfast protection, immeasurable kindness, and overflowing grace that have guided me throughout this remarkable journey. This study is dedicated to my cherished family, whose unwavering support has been a strong pillar of strength, nurturing me with love and encouragement in times of doubt. I also extend my heartfelt thanks to my devoted friends, whose relentless encouragement and belief in my potential have inspired and uplifted me at every twist and turn. I truly appreciate all those who have surrounded me with their kindness and unwavering faith in my abilities, for each of you has transformed this challenging yet gratifying research endeavour into a truly fulfilling experience.

Abstract

Introduction

Heavy metals present a significant global threat, and South Africa's mining industry exacerbates this issue due to its considerable contribution to environmental pollution. Toxic heavy metals such as Lead, Arsenic, Chromium, mercury, and Cadmium are not only hazardous but also carcinogenic when inhaled or ingested. This highlights the urgent need to assess the levels of specific heavy metals in soils near mine dumps and to quantify the associated health risks for children aged 1 to 12 years in Kagiso, West Rand. The study aimed to evaluate the risk of heavy metal exposure among children within this age group living in Kagiso, a township located in South Africa's West Rand District.

Method

A cross-sectional study was carried out in Kagiso involving the collection of 14 soil samples in a zigzag pattern to reduce variability. These samples were analysed at an independent and SANS 17025-accredited laboratory, ensuring the objectivity of the results. The data analysis utilized the Kruskal-Wallis and Wilcoxon rank-sum tests, both non-parametric methods. The main variables examined included concentrations of heavy metals and their respective collection sites. For this study, the researcher employed Stata 18.0. And a health risk assessment was conducted using the framework for Health Risk Assessment developed by the United States Environmental Protection Agency.

Results

The study revealed soil contamination, with variations in heavy metal concentration across collection sites. Cadmium (Cd), Chromium (Cr), and Nickel (Ni) were found in higher concentrations at the community site, soccer fields, excavation land and clinics, compared to the tailing dam. Chromium (Cr) levels exceeded South African and international reference values in all locations, and lifetime cancer risk from Cr exposure (1.04 E^{-05} to 1.93 E^{-05}) was above the US-EPA reference threshold. In addition, worst-case scenarios indicate significant risks from heavy metals (As, Ni and Cr) for young children. For those under 2 years, Chromium exposure was 2.35 $E^{-05,}$ and Nickel exposure is 1.36 E^{-05}. For children aged 2 to 6, Arsenic exposure is 1.4 E^{-05}, Chromium is 3.64 E^{-05}, and Nickel is 2.10 E^{-05}.

Conclusion

Heavy metal stressors, including As, Cd, Cr, Ni, and Pb, possibly originating from tailing dam facilities, cause soil contamination and pose significant health risks, particularly cancer due to Cr exposure, in children in Kagiso. However, no correlation was found between Cd, Cr, Ni, and Pb concentrations and distance from the tailing dam sites except for As that showed distance-related patterns. These findings highlight the need for further research and interventions to reduce these health risks.

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Table of Contents

Dedication iii

Abstract iv

Acknowledgements vi

Funding vii

Abbreviations and Acronyms xi

Definitions xiii

List of Figures xiv

List of Tables xv

CHAPTER 1: INTRODUCTION 1

1.1 Background 1

1.2 Problem Statement 4

1.3. Research Question: 5

1.4. Aim: 5

1.4.1 Specific objectives: 5

1.5 Justification: 6

1.6 Structure of the Report 6

CHAPTER 2: LITERATURE REVIEW 9

2.1 Introduction 9

2.2 Heavy Metals in the Environment 9

2.2.1 Sources and Distribution of Heavy Metals 9

2.2.2 Selected Heavy Metals of Concern 10

2.3. Sensitive Receptors and Exposure Pathways 13

2.3.1. Sensitive Receptor Locations 13

2.3.2 Exposure Pathway Analysis 14

2.4 Spatial Distribution of Heavy Metals and Proximity to TSFs 23

2.4.1 Impact of Proximity to TSFs on Soil Contamination 23

2.4.2 Distance-Decay Relationships 29
2.5 Health Risk Assessment (HRA) of Heavy Metal Exposure 30
2.5.1 The United States Environmental Protection Agency (USEPA) Frameworks for Health Risk Assessment 30
2.5.2 Cancer Risks from Heavy Metal Exposure 32
2.5.3 Case Studies on HRA Applications 34
2.6 Knowledge Gaps and Research Justification 35
CHAPTER 3: METHODOLOGY 38
3.1 Study Design: 38
3.2 Study Setting: 38
3.3 Sample collection: 41
3.4 Sample analysis 43
3.5 Data Management: 44
3.6. Data Analysis: 44
3.6.1. Wilcoxon rank-sum test and the Kruskal-Wallis test 45
3.6.2. Relationship between heavy metal concentration and distance from the TSF (objective 2): 45
3.6.3 Deterministic Health Risk Assessment Methodology (objective 3): 46
3.7 Quality Assurance Measures: 48
3.8 Ethical Consideration: 49
CHAPTER 4: RESULTS AND DISCUSSION 51
4.1 Heavy metal emission factors. 51
4.2 The correlation between the distances from the mining dump and selected places in Kagiso 55
4.3 Health risk assessment 57
CHAPTER 5: STRENGTH AND LIMITATION OF THE STUDY 65
5.1 Main findings: 65
Objective 1: 65

Objective 2:.....65
Objective 3:.....65
5.2 Strength of the Study.....66
5.3 Study limitations: 66
5.4 Future Research Avenue 68
5.5 Recommendations:.....68
CHAPTER 6: CONCLUSION 70
REFERENCES 71
APPENDIX.....90
Appendix A: Plagiarism declaration 90
Appendix B: Cancer slope factor for heavy metals[201 202].....91
Appendix C: Soil and dust ingestion rate[191].....92
Appendix D: 2024 South African school calendar for public schools[195].....93
Appendix E: The South African children's mean weight[197] 94
Appendix F: Waiver over ethics clearance of research.....95

Abbreviations and Acronyms

As	Arsenic
BW	Body Weight
Cd	Cadmium
CF	Conversion Factor
CR	Cancer Risk
Cr	Chromium
Cu	Copper
ED	Exposure Duration
EF	Exposure Frequency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
Fe	Ferrous
GIS	Geographic Information System
GPS	Global Positioning System
Hg	Mercury
HI	Hazard Index
HM	Heavy Metal
HRA	Health Risk Assessment
IARC	International Agency for Research on Cancer
IQR	Interquartile range
IR	Intake Rate
Kg	Kilogram
LADD	Lifetime Average Daily Dose

LT	Lifetime Expectancy
Mg	Milligram
Mn	Manganese
Ni	Nickel
Pb	Lead
SA	South Africa
SANS	South African National Standards
SF	Slope Factor
THQ	Target Hazard Quotient
TSF	Tailing Storage Facility
US-EPA	United States Environmental Protection Agency
WHO	World Health Organization

Definitions

Buffer Zone: Buffer zones are defined differently based on their intended use [1]. A buffer zone is a strip of land designated for a purpose, function, or zoning intended to shield one area of land from the effects of another [1].

Exposure: Exposure refers to the interaction between a stressor and a receptor, taking place at an exposure surface during a designated exposure period [2].

Exposure duration: "Exposure duration" refers to how long an agent interacts with a target, continuously or sporadically [2].

Exposure route: An exposure route is the exact way a stressor, like a chemical or biological agent, enters the human body (US-EPA, 1992) [2]. This can happen through inhaling during breathing, consuming it through intentional food choices or accidental ingestion, skin contact with surfaces, air, or products, or via injection [2].

Exposure receptor: An exposure receptor is an entity, such as an individual, organism, or ecosystem component, that interacts with a stressor during an exposure event [2]. These interactions can involve environmental factors like chemicals, physical agents, or biological pathogens, which may significantly impact the receptor [2].

Lifetime Average Daily Dose (LADD): The Lifetime Average Daily Dose (LADD) represents the dose rate averaged over a person's entire lifetime. This metric is relevant for substances that could exhibit carcinogenic characteristics or long-term effects. Generally, LADD is reported in milligrams per kilogram per day (mg/kg-day) or units of mass per mass-time [2].

Pollution: Pollution is the release of materials or energy into the environment in quantities or proportions that may be hazardous to people, animals, or plants [3].

Primary Data: Refers to information the researcher has gathered using a methodology created to address their research issue [4]. The initial user of the data is also the researcher or data collector [4].

Tailings Storage Facility: Tailings storage facilities, sometimes referred to as tailing dams, are engineering constructions consisting of restricting embankments and associated works [5]. They are responsible for managing related water resources and containing leftovers that remain after valuable material is removed from metal ore processing [5].

List of Figures

Figure 1 : A map showing the location of Kagiso township [179] 39
Figure 2: Location of Kagiso with industries and old facilities, with residential areas and tailings [180] 40
Figure 3: Kagiso community with tailing storage facility in the background (Photo credit : Jacques Tshunza) 40
Figure 4: Research team, while collecting samples (Photo credit: Jacques Tshunza) 41
Figure 5: Lifetime Carcinogenic Risk Estimation for Selected Heavy Metal Estimation for Selected Heavy Metals across various Sampling Sites 60
Figure 6: The Worst-case scenario Lifetime Cancer Risk Estimation in Kagiso 63

List of Tables

Table 1: Exposure route, acute effects and chronic effects of selected heavy metals 11
Table 2: Specific heavy metals with various sources 15
Table 3: Selected heavy metals sources, carcinogenesis and type of cancer caused 33
Table 4: Heavy metal of concern, route of entry, immediate and long-term effects 36
Table 5: Heavy metal of concerns with main exposure source and cancer type 37
Table 6: Collection sites categorized by their distance from the tailing storage facility and coordinates 43
Table 7: Parameters used for the Lifetime Average Daily Dose (LADD) and Cancer Risk in Children from 1 to 12 years 48
Table 8: Combined table of Maximal Allowable limit of Concentration of Heavy Metals Soil (mg/kg) FAO/WHO,EU, and South Africa with Average Concentration (mg/kg) of Heavy Metals in Different Locations 52
Table 9: Summary of Kruskal-Wallis test results 56
Table 10: Summary of the Wilcoxon rank-sum test 56
Table 11: The Estimated Lifetime Average Daily Dose (LADD) 58
Table 12: Slope Factor for Selected Heavy Metals[202 203] 58
Table 13: Parameters used for the Estimation of Worst-case Scenario 62

CHAPTER 1: INTRODUCTION

The chapter begins with thoroughly examining heavy metals and exploring their origins, which stem from natural geological processes and anthropogenic activities. It categorizes these metals according to their detrimental effects on the biosphere, emphasizing their widespread presence in ecosystems and varying toxicity levels. Additionally, the chapter provides a concise overview of the health implications associated with exposure to heavy metals, including both acute and chronic risks that can arise from contamination in various settings.

As the discussion unfolds, the chapter shifts to a broader perspective, analysing the global consequences of extensive metal pollution and illustrating how this issue crosses borders, affecting human health and the environment worldwide. It then narrows its focus to a specific region in South Africa, in the Gauteng province: The West Rand District Municipality. This section clearly outlines the motivation behind the study, elaborating on the pressing concerns related to metal pollution in this area.

Furthermore, it articulates the key questions guiding the research, identifies the main aim of the investigation, and specifies the objectives the study intends to accomplish. Through this structured approach, the chapter sets the foundation for an in-depth exploration of heavy metal pollution and its implications for local communities and the broader environment.

1.1 Background

Metallic components that have a relative density bigger than 5.0 and an elevated atomic number are called heavy metals (HM) [6]. Understanding the exposure pathway of heavy metals is crucial since they are found in various articles such as dye paints, culinary utensils, antiperspirants, fireworks, fertilizers, pesticides, wood preservation, cosmetics, barrier cream, medications, rubber, explosives, dentistry accessories, plastic, anti-dandruff shampoo, ink, and soaps. [7] [8]. Natural processes and anthropogenic activities such as manufacturing and farming are the primary cause of the release of heavy metals in water, soil and air. [9] [10].

Air pollution occurs when heavy metals are emitted as gasses, droplets, or microscopic particles [8]. These particles can settle close or travel a considerable distance depending on their size. When heavy metals are transported to various recipients by runoff or water bodies, water contamination results [8]. Soil contamination can occur from several sources, such as fertilizers, wastewater, mining waste, oil spills, or mishaps involving dangerous chemicals. It is crucial to remember that those nearby may be at risk of ingestion or inhalation from contaminated air,

water or soil [8]. Ingestion, inhalation and cutaneous are the most important routes of human exposure to heavy metals [11].

The World Health Organization (WHO) has recognized heavy metal contamination as one of the major environmental pollutants and subsequently classified it as a global challenge of critical concern [12]. Significant levels of heavy metals, like Arsenic (As), Chromium (Cr) VI, Ferrous (Fe), Manganese (Mn), Mercury (Hg), and Cadmium (Cd), exceeding global and regional standards for drinking water were found by a study conducted in Central Asia rivers. [13]. The study also found that Chromium (Cr) and Arsenic (As) (13) (12) were posing a significant cancer risk as the most widespread water pollutants (14). Additionally, another research study on heavy metal contamination in central Europe revealed disparities in heavy metal concentration in the flora across European cities [11]. The analysis of plant species revealed significant levels of Cadmium (Cd) in the leaves, while the root had high levels of Nickel (Ni) [11].These results reveal the potential detrimental heavy metal exposure to consumers of these plants. Another study conducted in Australia highlighted the significant adverse impact of heavy metal poison on human health and the natural environment [14]. According to Roy et al. [15], Africa had the lowest risk, indicating that Asia faces the most significant environmental and public health challenges from heavy metal pollution.

Furthermore, another research study in Cameroon underlined the effect of heavy rainfall on the level of heavy metal pollution in water [16]. This natural process significantly reduced the concentration of heavy metals [16]. A study in Zambia indicated alarming levels of heavy metal contamination of Zinc and Lead in sediments and soil secondary to anthropogenic activities such as mining. [17]. Significant Cadmium (Cd) pollution above acceptable limits was found in rivers in Zimbabwe [18]. The Omaruru River basin in Namibia was found to have high levels of Chromium (Cr) and Arsenic (As) sediment pollution [19]. Comparable studies in Angola [20], Botswana [21], and Mozambique (21) indicated that high levels of heavy metal pollution raise significant concerns about the challenge.

Harmful ranges of Chromium, copper and Nickel threatening some aquatic species were identified in urban river sediments in South Africa [22]. This significant pollution level is a big threat to the local biosphere and the health of aquatic species and communities that rely on these aquatic organisms for sustenance. Industrial activities were the first cause of the pollution, while wastewater effluent and vehicle exhaust [22] with urban runoff secondarily contributed to it. Another research on food safety in South Africa concerning culinary spices and herbs

indicated high levels of Chromium above reference values, but other parameters such as the hazard index (HI) and the target hazard quotient (THQ) ruled out the consumer's health risk [23]. These findings raise significant concern about the quality of the soils where these culinary herbs and spices grew and the kind of water used for irrigation.

For the Southern African region, the above findings indicate the severity of the adverse impact of heavy metal pollution, which should not be taken lightly. The biosphere pollution [24] exceeding acceptable limits, combined with the records of increased heavy metal production [25] , should raise significant concerns about heavy metal contamination. [26]. The benefit of these research results resides in the knowledge provided concerning health risks, including cancer associated with the consumption of heavy metal-contaminated groundwater [16]. Some heavy metal ions, including Chromium^{3+}, Copper^{2+} , Nickel^{3+}, Ferrous^{3+}, Manganese^{2+} , and Zinc^{2+} [12], are regarded as biologically significant when taken in smaller quantities for physiological processes such as metabolism, immunity, or other organic processes, classifying them as life-sustaining. Large amounts tend to be toxic [12]. Other heavy metals classified as unsafe for humans include Arsenic^{3+}, Cadmium^{2+}, Mercury^{2+}, and Lead^{2+}. [12]. These heavy metals are responsible for adverse health effects ranging from mild to severe organ failure, including nephropathy and hepatic disease, cancer, and death. [27]. Heavy metal pollution necessitates a multidisciplinary approach since it is a major cause of various neuropathies and systemic dysfunctions of the human body [11].

Environmental contamination by heavy metals is a serious concern in South Africa, mainly due to the country's extensive mining and industrial activities [28]. The study showed that millions of tons of waste were produced annually by South African mines, with about 47% coming from the gold mining industry [28]. More than 270 active mining dumps [28], also known as tailing storage facilities (TSFs), cover large surfaces of the Witwatersrand basin. These TSFs generate aerosols and chemicals contaminating environmental media such as air, water and soil [28].

The West Rand district municipality contains several tailings storage facilities (TSFs) [28]. Studies have identified many abandoned TSFs in the West Rand that are associated with uranium and gold mining activities and are located near populated communities [29] [30]. These TSFs contribute significantly to heavy metal pollution in the environment, making children more vulnerable to heavy metal exposure and high cancer risks than adults [31] [32] [33].

Another detailed study in the Witbank area of Mpumalanga, South Africa, adjacent to an operational coal mine, revealed concerning levels of heavy metal contamination [34]. The

research found that the average levels of several heavy metals were significantly above local reference values [34]. Specifically, the levels of Arsenic (As), Chromium (Cr), Manganese (Mn), Lead (Pb), and Nickel (Ni) exceeded the stringent South African guidelines designed to protect critical water sources from pollution [34].

Additionally, the study identified a significant public health concern: the cumulative cancer risks associated with exposure to Cadmium (Cd), Chromium, and Arsenic were alarmingly elevated for both children and adults, exceeding the unacceptable threshold of 1.00×10^{-4} [34]. The mean concentrations of these hazardous elements in the soil were found to be 0.40 mg/kg for Cadmium, an alarming 653.28 mg/kg for Chromium, and 19.44 mg/kg for Arsenic[34]. These concerning results emphasize the potential dangers of soil contamination and the threats it poses to agricultural products and consumers due to industrial activities. This situation raises important questions about the adverse effects on the surrounding environment and the health of local communities.

1.2 Problem Statement

Communities near mine dumps face possible health risks from heavy metals exposure in wind-blown aeolian dust and the surrounding soils. Mine activities, especially gold mining, often release heavy metals, such as Lead, Arsenic, Cadmium, Ferrous, Chromium VI, and Mercury, which can persist then accumulate in the environment affecting local ecosystems and public health [31]. Chronic exposure to these environmental stressors through direct contact with polluted soil, ingestion, or inhalation of re-suspended dust particles has been linked to adverse health outcomes, including neurotoxicity, organ damage and carcinogenicity [35]. Research has highlighted several challenges facing Gauteng, including clear evidence of the adverse effects of heavy metals on children' health [10]. Furthermore, there are inadequate control measures in areas where communities reside near mining dumps [29]. The lack of effective enforcement of buffer zone regulations, an essential requirement, is also prevalent in various regions of South Africa [36] [37]. For instance, in the West Rand, the Kagiso township is situated on or close to a tailings dump, despite the South African Chamber of Mines enforcing a 500-meter buffer zone [36].

Despite the significant environmental and public health concerns posed by chronic exposure to heavy metals, a gap exists in comprehensive health risk assessments that integrate the spatial distribution of the contaminants from the source to the receptor site using exposure pathway analyses and population vulnerability characteristics. This approach is critical, predominantly

for susceptible groups, together with youngsters, expectant mothers, the elderly, and individuals with pre-existing health conditions, who are more vulnerable to the detrimental effects of heavy metals.

To frame this problem, a multidisciplinary approach was employed and included [1] a determination of the spatial variation of the heavy metals pollution from the dump site to the receptor site; [2] soil sampling and analyses using standard reference methods to quantify metal concentrations; [3] health risk modelling using the USEPA guidelines to evaluate carcinogenic and non-carcinogenic risks, factoring in the ingestion exposure route; [4] vulnerability assessments using standard reference values for children (from birth to 12 years old) [38]. Previous studies have evaluated the health risks associated with heavy metal exposure in children globally but without specific age considerations and relationship between heavy metal concentrations and distances [31 35 37]. This current research will address these gaps. The aim is to assess the health risks linked to heavy metals in soils near mine dumps in Kagiso, West Rand, with a particular focus on children aged one to twelve years, who are more vulnerable due to their increased likelihood of soil ingestion.

1.3. Research Question:

What carcinogenic health risks do children aged 1 to 12 years in Kagiso, West Rand, face due to exposure to heavy metals in the soil near mine dumps?

1.4. Aim:

The study aims to evaluate the concentrations of selected heavy metals in soils near mine dumps and quantify the associated health risks for children aged 1 to 12 years in Kagiso, West Rand.

1.4.1 Specific objectives:

- To evaluate the concentration of specific heavy metals (Lead, Nickel, Arsenic, Cadmium, and Chromium) in soil samples collected from various sensitive receptor locations, such as schools, day-care and playgrounds, in Kagiso;
- To evaluate the relationship between different concentrations of selected heavy metals in soil samples from various collection sites and their distance from the tailing storage facility;

- To assess the cancer risk linked to children's (1 to 12 years) exposure to specific heavy metals in the soils of Kagiso using the United States Environmental Protection Agency (US-EPA) Health Risk Assessment (HRA) framework.

1.5 Justification:

The Witwatersrand Basin in South Africa is home to numerous mine tailings storage facilities, also called mine dumps, resulting from extensive mining activities [28]. These mining activities and resultant dumps have resulted in severe environmental degradation and public health challenges [28]. These dumps often contain high concentrations of stressors, including heavy metals, which pose long-term risks to nearby communities through soil, water and air contamination[29] [30]. One settlement that exemplifies the heightened variability of the communities due to chronic exposure to harmful mine dump stressors is Kagiso Township, located in the West Rand and situated less than 200 meters from a disused mine dump[39].

Children aged 1 – 12 years are more inclined to the harmful effects of exposure to heavy metals from soil through the ingestion route due to their frequent hand-to-mouth behaviour and higher soil ingestion rates than adults [40]. The proximity of Kagiso Township to the mine dump increases the likelihood of exposure to heavy metals through dermal contact, ingestion, and inhalation of re-suspended dust particles [39].

Despite these apparent risks, there is a paucity of information in the open and grey literature on local data quantifying the specific health risks related to chronic exposure to heavy metals in the soils of Kagiso Township and similar communities. This study is therefore critical to addressing this gap by providing an evidence-based understanding of the extent of contamination, exposure pathways, and health risks for vulnerable populations, in this case, children. Such findings will inform policy and guide mitigation strategies, especially concerning the prescription of buffer zones and management of mine dumps after decommissioning. The findings will also contribute to ongoing efforts to safeguard public health in areas impacted by historical mining activities in South Africa.

1.6 Structure of the Report

Chapter 1: Introduction

The chapter reviews heavy metals, their origins, and their environmental and health impacts. It highlights global metal pollution and focuses on the West Rand District Municipality in Gauteng, South Africa, outlining the study's rationale, research questions, and objectives. This

sets the stage for exploring heavy metal pollution's effects on local communities and the environment.

Chapter 2: Literature Review

This chapter delves into the origins and risks associated with heavy metals in the environment, particularly emphasising their presence near tailings storage facilities (TSFs) and the resulting soil pollution. It highlights the critical need for ongoing research and health risk assessments, especially concerning the contamination of crops and its implications for human health. Children are especially vulnerable to heavy metal exposure, which can compromise immune function and Lead to long-term health risks.

Chapter 3: Methodology

This section provides a summary of the research methodologies used in the study. It describes the study design and criteria for selecting representative locations. Further, it outlines the observations and sample collection techniques, clarifying how samples were obtained. It details the data management and analysis procedures, including the tools and statistical methods employed for accurate interpretation. Ethical considerations regarding participant rights are addressed, and quality assurance measures are highlighted to ensure the integrity of the research findings.

Chapter 4: Results and discussion.

This chapter presents a health risk assessment about children between the ages of one and twelve in Kagiso, West Rand, exposed to soils contaminated with heavy metals like Arsenic, Cadmium, Chromium, Lead, and Nickel. It highlights the varying concentrations of these toxins across different areas, noting the link between proximity to mining waste and higher metal levels.

The chapter also analyses estimated cancer risks for different age groups, focusing on the vulnerabilities of young children. Additionally, it compares these findings with relevant research to improve understanding of the health risks posed by environmental contamination in the region.

Chapter 5: Strength and Limitation of the Study

This chapter outlined the main findings of the study, highlighting the key outcomes that emerged from the analysis and their implications for environmental and public health. It also

outlines the strengths of the research, which enhance the credibility and robustness of the results, while acknowledging the limitations that may affect the interpretation of the findings. This approach offers a balanced perspective on both the contributions and constraints of the study. Additionally, the chapter explores potential avenues for future research, suggesting directions for advancing knowledge and addressing remaining gaps. Finally, it concludes with practical recommendations based on the evidence, aimed at guiding policy, practice, and further scientific inquiry.

Chapter 6: Conclusion.

In this chapter, the researcher offers a comprehensive overview of the study's scope, closely aligning with the objectives outlined earlier. Key findings are presented, along with their implications. Additionally, the researcher provides insightful recommendations based on these findings to inform future actions and decisions in the relevant field. This chapter also discusses the limitations of the study and suggests areas for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Studying heavy metal contamination in soil is a critical task, given the evidence that heavy metals may build up gradually over time, leading to significant risks such as soil degradation and potential contamination of crops. These risks can significantly affect human health. For instance, certain plants can absorb metals like Lead, Cadmium, and Chromium, which then enter the food chain, posing a direct threat to consumer well-being.

Heavy metal exposure presents a grave public health risk, particularly for children. Evidence suggests that children, with their growing bodies and unique behavioural characteristics, are more predisposed to severe health effects from heavy metals than grown persons. Furthermore, studies have established a clear link between heavy metal exposure and reduced immune function in children, highlighting the potential long-term health effects of this issue.

2.2 Heavy Metals in the Environment

2.2.1 Sources and Distribution of Heavy Metals

Research shows that heavy metals can come from both natural events and human activities, Leading to contamination in environmental mediums such as soil, water, air, and their interfaces [41]. This contamination results from various complex mechanisms [42]. Natural sources can include forest fires, which release metals stored in plants; [8] biogenic sources like microorganisms that mobilize metals; volcanic eruptions that discharge ash rich in heavy metals; and geophysical processes such as erosion and weathering of rocks, which set metals free as they degrade[40]. Additionally, meteorological events like dust storms and winds can carry heavy metals over vast distances, [43] while specific plants may release particles through their biological functions.

On the other hand, human activities significantly contribute to heavy metal pollution, often exceeding natural sources [44]. These include agricultural practices that involve fertilizers [42] and pesticides containing metals, emissions from coal-fired power stations that emit mercury and Arsenic, industrial activities that release metals during manufacturing, and mining operations that often contaminate nearby areas with extracted minerals. Moreover, the production and disposal [43] of batteries can introduce Lead and Cadmium into the environment, while household practices such as plumbing and poor waste management frequently allow heavy metals to leach into groundwater and surface waters [8]. Leaching from waste sites, storm-water runoff from

urban areas, and manure from agricultural operations further exacerbate the environmental load of heavy metals [8]. These contaminants introduce serious risks to environmental health and public safety by infiltrating soil and water systems [41].

It is crucial to emphasize that the Leading sources of heavy metal pollution are predominantly due to human actions rather than natural occurrences [44]. For instance, tailings storage facilities (TSFs) are significant anthropogenic sources of heavy metals, which has prompted an urgent concern from the World Bank and the United Nations Environment Program regarding their environmental and health risks [45] as evidenced by the World Bank's 2021 Good Practice Note on dam safety [5]. The note highlights that the chemical reactions in tailings, influenced by their mineralogical makeup and chemical characteristics, can release various hazardous substances. These include acidic water produced by sulphides oxidation, as well as heavy metals bound to clay particles, along with toxic gases [5 46]. The release of these contaminants can severely degrade soil and water quality, posing considerable risks to human health and ecosystem integrity [45].

2.2.2 Selected Heavy Metals of Concern

Recent research in South Africa has revealed that heavy metals, for example, Arsenic, Cadmium, Chromium, Nickel, and Lead, are present at concerning levels, exceeding acceptable limits [47]. This finding aligns with the International Agency for Research on Cancer's (IARC) classification of these heavy metals(Arsenic, Nickel, hexavalent Chromium, Cadmium) as Group 1 carcinogens [27 48].

Given these results, the current study has incorporated these heavy metals as significant areas of concern. Further research in this field is imperative.

Table 1 below highlights the harmful health effects associated with specific heavy metals.

Table 1: Exposure route, acute effects and chronic effects of selected heavy metals

Specific heavy metals	Exposure route	Acute effects	Chronic health effects
Arsenic:	Ingestion and inhalation are the reported routes of exposure to Arsenic [49].	Symptoms of immediate Arsenic exposure typically appear within 30 minutes and can include severe nausea, vomiting, abdominal pain, diarrhoea, weakness, and flushed skin[28] . As the condition worsens, individuals may experience muscle aches, confusion, hallucinations, seizures, and potentially coma or death[29] .	Chronic Arsenic poisoning typically shows symptoms around five years [31] after exposure, including skin pigmentation changes and hyperkeratosis on palms and soles. It is associated with serious health issues like skin cancer, diabetes, respiratory problems, cardiovascular diseases, kidney failure, and cognitive impairments in children[29] .
Cadmium:	People are exposed primarily through inhalation, with ingestion being the second most common route [5].	The impact of exposure differs based on the contact method. Symptoms from inhalation usually appear within 6 hours and can include fever, chills, breathing difficulties, and, in severe cases, death[30] . Consuming the substance causes gastrointestinal harm and may result in multiple organ failure [30] .	Cadmium builds up in the body throughout 25 to 30 years, Leading to various health issues, including osteomalacia, osteoporosis[31], genetic defects, and several types of cancer, such as stomach, breast, lung, and kidney cancers. Moreover, it can also adversely affect the immune system [32] .

Chromium	Research shows Chromium exposure mainly occurs through inhalation, ingestion, and skin contact. Inhalation presents the most significant risk for workers, while ingestion is more frequently observed in the general public [33]. The health effects vary depending on whether Chromium is in its III or VI form [33].	Inhaling Chromium VI can cause occupational asthma. Large amounts can impact multiple organs, including respiratory, cardiovascular, gastrointestinal, haematological, neurological, and hepatic systems, Leading to severe health issues or fatalities[34].	Chromium III is not carcinogenic but can cause respiratory inflammation and pose risks to a developing foetus if inhaled[34]. Chromium VI, a known carcinogen, can cause health issues when inhaled, including nasal septal ulceration, respiratory inflammation, lung cancer (latency over 20 years), and kidney problems. Skin contact may result in allergic and chronic dermatitis [33] [34] . Simultaneously, skin exposure can Lead to allergies and chronic dermatitis[34].
Lead	Someone can be exposed to Lead in three ways: breathing, swallowing, or absorbing it through your skin[35].	Dosage effects can vary: A high dose may result in anorexia, nausea, vomiting, stomach pain, sleepiness, and potential liver or kidney damage [50]. A considerable dose could Lead to muscle contractions, convulsions, decreased vision, and possibly death [50].	Lead exposure can enter the body in different ways, causing cognitive issues and hindering growth, especially in children under six [35]. It can negatively impact several organs and systems, including the heart, kidneys, bones, teeth, reproductive system, immune system, and nervous system [35] [36] .
Nickel	The three main ways receptors can be exposed are skin contact, breathing, and ingestion [37].	Inhaling this substance may Lead to severe respiratory and kidney issues[37] . Ingesting it might cause symptoms such as nausea, vomiting, diarrhoea, and neurological impairments[37] .	Dermal exposure can cause dermatitis [37]. Inhalation exposure may Lead to asthma, reduced lung capacity, bronchitis, nasal ulcers and lung cancers[37].

2.3. Sensitive Receptors and Exposure Pathways

2.3.1. Sensitive Receptor Locations

Research conducted across various mining districts in South Africa has consistently highlighted higher levels of heavy metals found in soils[34], demonstrating the urgent need for further investigation[31 32 33 47]. Although the specific contaminants varied, studies conducted in preschool facilities in Cape Town detected notably high levels of zinc and Arsenic [51]. Similarly, research in a district of the Free State Province identified increased levels of copper, Cadmium, Lead, Nickel, and zinc [52]. Furthermore, investigations in Krugersdorp [31], a mining town, along with two mining communities in Gauteng West Rand District [47], found heightened levels of Arsenic, Cadmium, cobalt, and Nickel.

These findings suggest that exposure to heavy metals extends beyond miners to their families, affecting vulnerable people such as expectant mothers and seniors, individuals with chronic diseases, and children. Such exposure raises concerns regarding potential risks to health and development. These results highlight the critical importance of ongoing research into the public health implications of heavy metal contamination.

A 2025 report emphasizes that children aged one to five years are more susceptible to environmental toxicants than adults for several reasons [40]:

- Increased Consumption: Children intake more food, water, and air relative to their size.
- Ineffective Detoxification: Their bodies are less adept at breaking down and eliminating toxins.
- Proximity to Contaminants: Being closer to the ground exposes them to soil and dust contaminants.
- Hand-to-Mouth Behaviours: Their natural inclination to put hands and items into their mouths raises the risk of ingesting harmful substances.
- Anatomical Vulnerabilities: Features such as developing airways and more absorbent skin contribute to their increased sensitivity.
- Rapid Development: The ongoing development of their organs and body systems amplifies their vulnerability during this critical stage.

These factors significantly elevate children's risk from environmental hazards, including heavy metals, compared to adults.

2.3.2 Exposure Pathway Analysis

Table 2 presents an analysis of the diverse sources of heavy metals, emphasizing the critical factors that drive their presence in our environment. It illustrates how the release and emission of specific heavy metals are fundamentally linked to the activities associated with each source, demonstrating the profound impact of human behaviour on environmental health.

Table 2: Specific heavy metals with various sources

Heavy metal	Source	
	Natural	**Anthropogenic**
Arsenic	Lithosphere, weathering, volcanic eruption, mineral ores, and long-term geochemical changes [53 54 46].	Mining activities, burning of fossil fuels, metallurgical, ceramic, and smelting sectors, rock sediments, dye industries, and those that manufacture fungicides and pesticides, smelting of gold, pharmaceuticals, wastewater management, and metal hardening [53 54 46].
Cadmium	No natural sources reported	Tobacco products, non-ferrous smelters, industrial processes involving Cadmium, incineration of municipal waste and sewage sludge, nuclear fission reactors, welding, electroplating, insecticides, PVC products, motor vehicle tire wear, colour pigments, electronics, pesticides, paints, batteries, mining and metallurgy, wastewater, and phosphate fertilizers [53 54 46]
Chromium	Rock and aquifer materials [53 54 46].	Rubber, textile, tannery, and photographic industries; textile industry; metal plating, paints, pigments; rubber, photography, motor vehicle oil burning, chemical industry, leather industry, industrial dust and fumes; fertilizers, mining, metallurgy, and car exhaust smoke [53 54 46].
Lead	Earth crust [46 55]	Lead gasoline, electronic waste, vehicle emissions, wastewater, manufacturing of Lead-acid batteries, pesticides, coal burning, mining and metallurgy, some types of PVC, urban runoff, paints and pigments, fertilizers, and solid waste [46 55] .
Nickel	Windblown dust, volcanic ash, wildfire smoke, and meteoric dust [56 46] .	Fertilizers, iron and steel production, industrial aerosols, battery production, zinc-based casting, electroplating industries, food processing, chemical industries, waste incineration, mining and metallurgy, and coal combustion [56 46].

Heavy metals threaten our environment by contaminating aquatic systems, soils and sediments from natural and human activities [46 41]. Volcanic activity and industrial pollution emit these harmful metals into the atmosphere, where they can precipitate and harm soil and water quality

[41]. They bioaccumulate in organisms [43], disrupt ecosystems, and contaminate groundwater, affecting critical water supplies [8 41].

The transportation and outcome of heavy metals in the biosphere can be delineated through five essential steps [57 58]:

- **Source:** The point of origin responsible for releasing pollutants into the environment [8 57 59] The current study identifies the Tailings Storage Facility (TSF) as the potential primary source of the selected heavy metals found in Kagiso.
- **Transport Media** is crucial in the movement of pollutants [57 60]. These various mediums, such as air, soil, and water, facilitate the transport of pollutants, enlightening us about the diverse pathways through which pollutants can spread in the environment [57]. This study will specifically focus on soil as a transport medium.
- **Exposure Point:** The specific location where a receptor, such as a human or an ecosystem, comes into contact with the pollutant, Leading to potential harm or disruption [57]. In the current study, the identified exposure points include the mine tailings storage facility, local communities, primary schools, soccer fields, and day-care facilities.
- **Exposure Route:** The mechanisms by which pollutants penetrate an organism [57]. This can transpire through inhalation (breathing), ingestion (eating or drinking), involuntary consumption of pollutants, or dermal contact (absorption through the skin) Leading to entry into the bloodstream [57 61]. This study will focus specifically on the exposure routes of inhalation and ingestion.
- **Receptors:** The entities exposed to pollutants, which encompass men, women of childbearing age, the elderly, individuals with compromised immune systems, and children [57 62]. Receptors can also include various organisms and plants in the environment and the soil and water systems [63 57]. In the current research, the focus is specifically on children aged 1 to 12 years as the primary receptors of these pollutants.

The source-receptor model

The source-receptor model outlines the exposure process through five key components: release, emission, transmission, immission, and exposure event [64]:

- **Release** is the liberation of a stressor through natural or human-induced processes, characterized either by dispersion or as mass per unit area [65 64]. In the context of the

current study, release can be defined as the liberation of selected heavy metals due to weathering, windblown dust, or the dumping of materials from mining processes.

- **Emission** transfers a stressor to a compartment, such as workplace air, and is measured as flow (quantity per unit of time or area) [66] [64]. In this study, emissions refer to the transfer of selected heavy metals in water, soil, or air.
- **Transmission** channels the stressor to the receptor via a medium, relying on methods like ventilation and absorbent materials to minimize impact [10] [64]. In this study, transmission refers to the movement of selected heavy metals through mediums like air, water, or soil.
- **Immission** introduces a stressor into the receptor's immediate area, typically measured by concentration or energy/pressure levels [67] [64]. In this research, immission introduces selected heavy metals into the immediate environment of children aged 1 to 12 years.
- **Exposure Event** describes the interaction of the stressor at an exposure surface over an extended period, quantified as concentration or energy/pressure multiplied by the duration of exposure or as a time-weighted average (TWA) [68] [64] . In this study, the exposure event refers to the interaction of selected heavy metals at the oral or nasal mucosa over a certain duration.

Fate through different environmental media can be summarized as follows:

Upon the release of pollutants into the atmosphere, various scenarios may unfold [69] [70]:

- Pollutants can travel extensively through the atmosphere, increasing the risk of inhalation by humans, animals, and plants [70]. This spread is particularly noticeable during the day when solar heating warms the air, promoting the dispersion of pollutants [71]. In contrast, cooler night-time temperatures stabilize the atmosphere, resulting in reduced movement and lower dispersion of these contaminants [71]. Additionally, geographical features such as mountains, elevated terrain, and valleys can influence the distribution of pollutants by acting as barriers [72]. Various meteorological factors, including wind speed and direction, as well as rainfall, [73] can carry pollutants over long distances and assist in removing them from the atmosphere or dissolving gaseous contaminants, thereby reducing overall pollutant concentrations in the air.
- Depositional processes can occur via two pathways [70]:
    - Direct deposition onto [74] vegetation, soil, or surface water [48] subsequently influences groundwater, surface water, or sediments [70].

- Indirect deposition via transportation through alternate media, such as runoff [70].

Chemical or physical transformations of pollutants may take place [70].

- When pollutants are introduced into the soil, three fundamental scenarios may arise. [75]:

- Migration: Through erosion or runoff, thereby impacting surface soil, surface water, and sediments [75] [76].
- Resuspension and Deposition: This may result in plant uptake, inhalation by people and animals, accidental ingestion or affect surface water and sediments [77] [75].
- Leaching: This impacts subsoil, groundwater, surface water, and sediments [78] [79] [75].
  - Waterbody contamination can happen through two different processes:
- Direct discharges from Industries, commercial sites or residential areas.
- Indirect discharge migrating from groundwater, stormwater runoff, or deposition of pollutants from the atmosphere [80] [81].

Waterbody pollutants can migrate downstream to rivers and estuaries or sink to sediments. Direct exposure can occur via drinking water or sediment through ingestion and dermal contact, while indirect exposure can occur through a contaminated food chain [81] [82] [83].

The conclusive phase of exposure transport and fate culminates in direct exposure to potential receptors and indirect exposure through the food chain, affecting aquatic animals, organisms, and plants, as well as semi-aquatic and terrestrial animals.

Immission and factors facilitating the uptake

The process of bringing a stressor into proximity to a receptor is known as "immission," it is frequently typified by varying degrees of energy, pressure, or concentration. [64] [84]. This phenomenon happens when outside factors infiltrate a receptor's surroundings and may impact its behaviour or well-being. In the context of the current study, examples of immission include wind blowing dust onto surfaces near children or food becoming contaminated with soil brought into the children's microenvironment.

Immission encompasses many pollutants that can impact our health and environment, including air contaminants, noise, vibrations, light, heat, radiation, and electromagnetic fields [85] [67]. Emissions originating from sources such as industrial facilities and various modes of

transportation align with the well-established source-receptor model [64], which illustrates how these pollutants interact with the surrounding environment.

It is crucial to consider the distinct conditions that arise based on the pollutants' chemical, biological, or physical characteristics as they travel through the air or other media [67 86]. There are tailored management strategies for specific pollutants designed to mitigate their effects [67]. For example, airborne emissions can be significantly reduced by strategically implementing tall chimneys or advanced filtration systems [67 87] While sound barriers can serve as effective shields against pervasive noise pollution, it is essential to emphasise that high-frequency sounds and magnetic fields possess the ability to penetrate solid structures, rendering them particularly challenging to block. This highlights the complexity of managing pollution and the need for comprehensive approaches to safeguard our environment and well-being.

Research is conducted to establish the acceptable limit for each type of atmospheric emission found in the air [88]. This process determines the maximum allowable concentration of a pollutant to prevent toxic effects and mitigate its possible impact on human health and the wider biosphere [88].

In this study, we focus on the immission of specific heavy metals, including Pb, As, Cd, Cr, and Ni, into the environments where children aged 1 to 12 years live, learn, and play. It aims to investigate the potential effects of these contaminants on the health and development of young children, highlighting the importance of understanding exposure pathway and the risks associated with heavy metal contamination in residential and recreational areas.

Factors facilitating uptake

Heavy metals can enter and accumulate in plants and animals through various intricate processes [89]. The absorption and build-up of these toxic elements in plants are significantly influenced by a delicate interplay between the plants' physiological traits and the specific properties of the soils they thrive in [89 90]. Among the essential soil characteristics that govern this process are soil pH and heavy metal concentration [91], which determines the solubility of metals; redox potential, which affects the chemical forms of the metals present; organic matter content, which can sequester metals and impact their bioavailability; clay content, which improves the soil's capacity to retain and exchange essential nutrients while enhancing cation exchange capacity, which measures the soil’s ability to retain positively charged ions, including heavy metals [89].

Heavy metals persist in the environment as formidable pollutants, gradually accumulating within living organisms and creating a cascading effect through food chains as they transfer from one trophic level to another [92]. The level to which these metals accumulate within organisms is shaped by their rates of absorption and elimination, which can vary greatly depending on numerous reasons [92 93]. These influences comprise the specific chemical form or speciation of the heavy metal in question and the complex physiological mechanisms that various organisms have evolved to manage these toxins [92 94 95]. These mechanisms allow organisms to maintain homeostasis and effectively detoxify harmful substances, displaying nature's remarkable adaptability in light of environmental challenges.

Exposure routes: Soil or dust ingestion, dermal contact, and inhalation

A pollutant may enter an individual's body through three distinct ways called exposure routes: ingestion, inhalation, and dermal contact [68]. However, this section will concentrate on soil ingestion, dermal contact, and inhalation.

- **Soil or dust ingestion** [96]:

Ingestion of soil or dust can occur intentionally, known as geophagy or pica, or inadvertently through hand-to-mouth contact [97]. It can also happen via another medium, such as food that has absorbed soil or dust [98]. A recent study indicates that young children are the primary demographic for ingesting large amounts of soil and dust, followed by infants, adolescents, and adults [99 100].

The following steps outline a systematic approach to estimating an individual's average daily dose of a contaminant through ingestion [96 101 102103]:

- Determine Contaminant Concentration: Begin by assessing the level of the pollutant present in the medium, which may be quantified in units such as milligrams per Litre (mg/L) or milligrams per gram (mg/g). Subsequently, this concentration is multiplied by the individual's ingestion rate, expressed in Litres per day (L/day) or grams per day (g/day). This calculation will yield the total amount of contaminant ingested over a specified timeframe.
- Calculate Total Exposure: In the next step, multiply the result obtained from the first calculation by the frequency of exposure, which indicates the annual number of days the individual is likely exposed to the contaminant. Further, multiply this result by the

exposure duration, representing the total number of years of exposure. This comprehensive calculation will provide the overall exposure over time.

- Estimate Average Daily Dose: To derive the average daily dose, divide the total exposure calculated in the previous step by the product of the individual's body weight (measured in kilograms) and the average period considered (expressed in days). This division will estimate the average daily dose of the contaminant experienced by the individual.

By adhering to these steps, one can attain a detailed understanding of the effect of the contaminant on a person's daily exposure, considering critical factors like ingestion rate, concentration, and body weight.

Dermal contact

Dermal exposure occurs when harmful substances such as chemicals, toxins, or irritants come into direct contact with the skin [104] [35]. As the body's largest organ, the skin is a vital barrier. However, when compromised or subjected to specific harmful agents, it can Lead to adverse health effects [104] [105]. These effects can range from localized issues, such as allergic dermatitis and skin irritation, to more systemic responses, where toxins penetrate deeper layers and enter the bloodstream, potentially resulting in significant health problems [104] [105] [106]. Understanding the mechanisms and risks associated with dermal exposure is essential for developing effective safety protocols and protective measures in environments with these hazards.

Dermal exposure to outdoor soil and dust can occur during various activities, including gardening, construction work, and recreational pursuits [107]. Additionally, individuals may experience indoor exposure through dust accumulating on floors, clothing, or surfaces [104].

Estimating dermal exposure necessitates understanding various factors, including the level of the pollutant in the medium that contacts the skin and the occurrence and extent of that contact. [104] [108]. Additional considerations that influence dermal exposure include the surface area of the dermis and the tendency of solid particles to adhere to the skin's surface [104] [109] [110].

- **Inhalation**:

Inhalation exposure [111] [112] occurs when a person breathes in air laden with various hazardous components, including particulate matter, fine dust particles, vaporous substances that may be volatile or semi-volatile, and aerosols, tiny droplets suspended in the air. This type of exposure is particularly concerning as individuals may encounter these airborne pollutants during a wide

range of indoor and outdoor activities [111 113]. For instance, while enjoying leisure activities in a park or engaging in household chores, one may unknowingly inhale harmful substances [111]. Additionally, indoor occupants are vulnerable to outdoor air contaminants that can infiltrate their homes, compounding the risk [114].

To accurately estimate inhalation exposure and enhance our understanding of individual risks, it is essential to consider several key parameters [111 115]:

- The contaminant level: Measured in milligrams per cubic meter (mg/m^3), this parameter indicates the concentration of the contaminant in the air.
- The inhalation rate: This refers to the volume of air inhaled, expressed in cubic meters per hour (m^3/hour), which can vary based on individual activity levels and characteristics.
- The duration of exposure: This defines the number of hours per day an individual is exposed to the contaminant.
- The frequency of exposure: This indicates the number of days per year during which exposure occurs.
- The total exposure duration: Expressed in years, this offers a long-term perspective on exposure.
- The individual body weight: In kilograms (kg), body weight influences how the organism absorbs and metabolizes the contaminant.
- The average time: Measured in days, this parameter assists in finalizing the dose estimation.

Considering these factors is essential for a thorough assessment of inhalation exposure risks.

Specific relevance of pathways for children

A report published in 2025 indicates that children aged 1 to 5 years exhibit heightened susceptibility to environmental toxicants compared to adults due to several underlying factors [40]. Firstly, children consume more food, water, and air relative to their body size than adults, which supports their rapid growth and development by providing essential nutrients, hydration, and oxygen [40 116 117 118]. Secondly, their propensity for hand-to-mouth behaviours increases the likelihood of ingesting harmful substances [40]. Furthermore, research findings reveal that the main route of exposure to numerous chemicals in children arises from food ingestion [119].

2.4 Spatial Distribution of Heavy Metals and Proximity to TSFs

2.4.1 Impact of Proximity to TSFs on Soil Contamination

The established buffer zone [38], mandated by the South African Chamber of Mines, is now under scrutiny, challenged by emerging research findings that question its effectiveness in ensuring the well-being and safety of local communities. A notable example of this concern is a study that meticulously analyses the sediments found in dams within a few kilometre radius of a mining area in East Rand [37]. This research reveals troubling implications about the adequacy of the buffer zone in safeguarding the biosphere and the health of those living near mining operations [37]. Additionally, the study revealed that sites closer to mine dumps and other sites situated more than 500 meters away from a collection of mine dumps and tailings had higher levels of heavy metals, including Lead and Cadmium, which are known to cause health issues [37]. Furthermore, an investigation on residents living within a radius of one to five kilometres (km) from mining dumps in Gauteng and the North West Province of South Africa exhibited comparable findings, highlighting a significant correlation between the prevalence of allergies and proximity to mine tailing dumps [29]. Specifically, individuals residing within a radius of one to two kilometres from these dumps experienced a higher incidence of allergic reactions [29]. Further studies revealed that wind can transport respirable particulate matter, including harmful toxins, over distances up to 20 kilometres from the source [36]. This raises concerns about the broader impact of mining operations on community health and air quality in these regions.

Research indicates that communities near tailing storage facilities in South Africa, especially in the West Rand area, face an increased risk of exposure to various harmful contaminants, such as toxic heavy metals [63 120]. Alarmingly, there is a significant lack of studies focused on the particular health hazards that heavy metal pollution poses to vulnerable children in the West Rand region [63 120].

These factors highlight the critical necessity for thorough research to evaluate the health threats children in Kagiso might encounter due to heavy metal exposure in the soil [63 120]. Recognizing these risks and developing effective control measures and mitigation strategies is essential to address and reduce this urgent environmental issue.

Factors influencing heavy metal distribution

A comprehensive study conducted in Northeast Morocco examined the environmental impacts of mine tailings and the adjacent soils around an abandoned Lead mine [121]. This research demonstrated the critical function of the physicochemical characteristics of the contaminated tailings and the surrounding soils in determining the distribution of harmful pollutants [121].

The study highlighted how the region's distinctive geological characteristics and the specific types of ore being extracted, notably Lead-rich deposits, significantly influence the local potential of hydrogen (pH) levels [121]. These pH levels affect the bioavailability and solubility of various metals, which can have profound implications for local ecosystems and human health [122] [123].

Moreover, the investigation revealed a significant gradient in the levels of heavy metals, including Lead (Pb), copper (Cu), zinc (Zn), Arsenic (As), and Cadmium (Cd), as one moves further away from the tailing storage facility [121]. This finding illustrates the spatial effects of mining activities on soil health, confirming that pollutants diminish with distance.

Literature has indicated that the following factors can affect the dispersal of heavy metals:

The physicochemical properties of soils

The soil's physicochemical characteristics are vital in determining its quality and fertility [123] [124] [125] [126]. Key factors include the soil's pH level, which indicates its acidity or alkalinity, and electrical conductivity, which reflects its ability to conduct electrical currents and, thus, its salinity [123]. Additionally, the concentration of organic matter is vital, as it enhances soil structure and nutrient availability [124]. Furthermore, essential macronutrients such as nitrogen, potassium, and phosphorus directly influence plant growth and overall ecosystem health [124]. Each component interacts to create a complex environment that supports life and influences agricultural productivity [122]. Soil’s physicochemical properties comprise pH [126], electrical conductivity, organic matter levels, and quantities of macronutrients such as nitrogen, phosphorus, and potassium [124].

Heavy metals in soil appear as adsorbed particles, inorganic and organic compounds, salts, colloids, and hydroxides or oxides [123]. In acidic soils, a rise in pH is associated with a reduction process [124] [127]. During a neutral state, protons are reduced to promote this reduction. Conversely, pH decreases during oxidation [127]. A low pH promotes the release of heavy metals,

increasing their mobility and reducing their availability in the soil [123]. Conversely, higher pH levels result in lower mobility and greater availability of heavy metals in soil [122].

Heavy metals in soil exist in various forms, including adsorbed particles, colloids, inorganic and organic compounds, salts, hydroxides, and oxides [123]. The soil's pH level can significantly influence the behaviour and mobility of these metals [122].

Heavy metals are released from solid phases when the soil has a low pH, increasing their mobility [128]. This heightened mobility often increases the risk of heavy metals leaching into groundwater or being absorbed by plants, posing potential risks to the biosphere and human health [122 129]. On the other hand, when pH levels rise, the solubility of heavy metals decreases, Leading to reduced mobility and increased retention of these metals in solid forms [127]. As a result, the bioavailability of heavy metals may decline, lowering the potential for their uptake by organisms [122 129].

Additionally, another study showed that the region's distinctive geological characteristics and the specific types of ore being extracted, notably Lead-rich deposits significantly influence local pH levels [121].

The total phosphorus [129 128 126] reveals a noteworthy and significant positive correlation with several specific heavy metals, including zinc (Zn), Lead (Pb), Arsenic (As), and Cadmium (Cd) [130]. Research has demonstrated that, while the mobility of Arsenic in soil less than 50 centimetres deep may be inherently limited due to its chemical properties, introducing phosphorus fertilizers profoundly enhances the movement and availability of this element within the soil matrix [130 127].

In addition, zinc in phosphate fertilizers plays a critical role in the soil's chemistry, as it competes with Cadmium for the same binding sites. This competition can result in a notable increase in Cadmium concentration within the soil solution, potentially impacting soil health and ecosystem dynamics. [130].

Potassium typically correlates negatively with specific heavy metals, notably Nickel and copper [130 126]. This relationship suggests that as potassium levels increase, the concentrations of these heavy metals tend to decrease [128 131]. Copper, in particular, has a strong propensity to bind with organic matter, which is attributed to its unique chemical properties [130]. This affinity for organic compounds is more significant than many other heavy metals, influencing its behaviour in environmental processes such as soil chemistry and nutrient cycling [130].

Understanding these interactions is crucial for assessing soil health and managing contamination in agricultural and natural ecosystems [130].

Nickel (Ni) and copper (Cu) are vital nutrients in the intricate process of plant growth and expansion [130 131]. Nevertheless, it is crucial to note that various plant species exhibit distinct absorption levels and demand for these trace elements, reflecting their unique physiological needs and adaptations [130].

Research reveals a significant positive relationship between soil organic matter and total nitrogen content, highlighting the importance of healthy soil in sustaining plant life [130 131 126]. In contrast, the connection between soil organic matter and heavy metals appears minimal, indicating that these harmful elements do not significantly interact with organic components [130].

Furthermore, a comprehensive analysis of the complex interactions between soil nutrients and heavy metals highlights that the uptake of organic matter and vital nutrients such as nitrogen, potassium, and phosphorus often coincide with the soil's ability to retain heavy metals [130 131]. This retention can result in detrimental soil contamination, driven by processes like diffusion and the gradual accumulation of erosion over time, ultimately threatening plant health and the broader ecosystem [130].

Weathering Severity

The extent of weathering plays a critical function in determining the geochemical behaviour of heavy metals like Arsenic (As), Cadmium (Cd), Lead (Pb), and zinc (Zn) [123 132 133 134]. As weathering processes become more pronounced, there is a notable increase in the concentrations of these heavy metals within the soil matrix [123 134]. This increase can be attributed to the breakdown of minerals in the parent rock material, which releases these metals into the soil environment [123].

To effectively assess the degree of weathering, evaluating the type of soil parent material is essential [123 134]. Different materials undergo weathering at varying rates and release metals in differing concentrations [123]. By understanding the parent material, we can gain insight into the potential for metal accumulation in the soil [123].

Wind blows and surface runoff:

Numerous studies have provided compelling evidence of wind and surface runoff's role in redistributing heavy metals in soil ecosystems [135] [136] [137]. For instance, research conducted near mining operations indicated that copper, zinc, and Lead were found in significantly higher concentrations in downwind soils, highlighting the impact of airborne particulate matter released during extraction and processing activities [135]. Furthermore, another study demonstrated that prevailing wind patterns also influenced the accumulation of Arsenic and Cadmium, as these metals can become airborne and settle in surrounding areas [135] [137].

In addition to atmospheric dispersion, surface runoff has become a significant pathway for transporting heavy metals [135] [138] [139]. A thorough investigation revealed that dissolved heavy metals, including Cadmium, Lead, and Chromium, are swiftly released from mining areas during precipitation events [135]. This release allows these metals to infiltrate previously untainted soil regions, resulting in markedly elevated concentrations of these toxic substances [135]. Such contamination poses serious risks to soil health, negatively impacting its structure, fertility, and biological activity, all essential for supporting plant growth and agricultural productivity [135].

Furthermore, the consequences extend beyond the immediate vicinity of mining sites, as these heavy metals can accumulate throughout the broader ecosystem, potentially affecting water quality and harming aquatic life [135]. Another study indicated that Cadmium (Cd) primarily migrates through surface runoff [140]. At the same time, Lead (Pb) and Chromium (Cr) enter soil systems through atmospheric deposition, including dust particles, precipitation, and surface runoff [135]. These discoveries highlight the urgent need for effective management strategies to reduce the release and spread of heavy metals in mining-impacted areas.

Impact of plant sorption and uptake on soil heavy metals

Extensive research has explored the effects of toxic heavy metals on plant growth and the ability of specific vegetable species to mitigate soil contamination. Notably, plant species such as Allium cepa (commonly known as onions), Daucus carota (carrots), flax (Linum usitatissimum), kenaf (Hibiscus cannabinus), various Populus species (often referred to as poplar trees), and Pisum sativum Linn (garden peas) have been shown to significantly reduce heavy metal concentrations in contaminated soils through a process known as phytoremediation [141] [142] [143] [144].

Phytoremediation involves using plants to absorb, accumulate, and stabilize harmful contaminants from the soil and water, effectively improving soil health and restoring ecosystems [142]. These studies highlight the critical role that these plants can play in environmental remediation efforts [141 142 143 144]. However, they also raise important concerns regarding the safety of consuming these vegetables [141 144] when grown in polluted environments, as they may accumulate harmful levels of toxic metals in their tissues. Therefore, while these plants present a promising solution for enhancing soil conditions, caution is warranted regarding their consumption when sourced from contaminated areas.

The existence of additional sources

Recent research highlights the critical importance of identifying and assessing various sources of heavy metals that significantly impact their distribution in the study area [130 145 146 147 148 149 150]. These sources are diverse and include:

- Sewage Irrigation: This practice can leach harmful contaminants, including heavy metals, into the soil. This not only affects soil quality but also poses risks to crops and groundwater.
- Agricultural Chemicals: The application of pesticides and fertilisers can introduce harmful substances such as Cadmium, Lead, and Arsenic into the environment. Certain agricultural practices, particularly those involving treating wastewater, can further exacerbate metal accumulation in soil and plants.
- Vehicle Emissions: Exhaust from vehicles is an essential source of heavy metals like Lead and zinc. These pollutants are released into the atmosphere and eventually settle onto soil and water bodies, disrupting local ecosystems.
- Gasoline Transport Activities: The transportation of gasoline carries the risk of accidental spills and leaks, which can contaminate soil and water sources with hydrocarbons and heavy metals, impacting human health and the ecosystem [130 145].

These factors interact in complex ways, shaping the environmental landscape and complicating the problem of heavy metal pollution in the area [130].

For instance, a detailed study indicated that the levels of Chromium and Nickel in the soil were mainly due to the geological parent material and industrial activities related to the non-ferrous metal industry, which often involves mining operations and metal processing facilities [145].

Other investigations revealed that agricultural practices were primarily responsible for elevated zinc, copper, and Cadmium levels [130] [146] [147] [148]. These levels were further intensified by emissions from automobile exhaust, coal mining operations, and atmospheric deposition from combustion processes, all contributing to heavy metal accumulation in soil and localized water bodies [130] [149] [150].

Notably, the spatial distribution patterns of Chromium and Nickel exhibit remarkable similarities, as both metals originate from similar sources influenced heavily by industrial activities and urban development [130]. This relationship emphasises the need for comprehensive approaches to monitoring and mitigating heavy metal contamination to protect the local environment and community health.

2.4.2 Distance-Decay Relationships

A comprehensive study assessing Cadmium and Lead contamination in the soil of mining areas, alongside the subsequent accumulation of these metals in selected plant species within a gold mining region in Tongguan, demonstrated a significant decline in Lead and Cadmium concentrations as the distance from the mining site increased. [151]. The findings of this research demonstrate the effectiveness of phytoremediation, where plants are utilized to extract or stabilize contaminants. [151]. They also indicate that the distance from the source of contamination is essential for reducing heavy metal levels in the soil. [151].

In a related investigation conducted in Murgul, Turkey, researchers analysed the presence of various heavy metals in soil and sediment samples [152]. Their findings revealed that the concentrations of certain heavy metals, including Chromium, Lead, and zinc, exhibited a clear decreasing trend with increasing distance from the mining operation [152]. This suggests that remediation efforts may be more effective in areas further away from immediate contamination sources [152].

Furthermore, a targeted study on Cadmium levels in Lead-zinc mining regions of Northeast China confirmed that greater distances from mining activities were associated with lower Cadmium concentrations in the surrounding soil and vegetation [153]. This reinforces the understanding that proximity to mining operations significantly influences environmental metal accumulation [153].

Additionally, an evaluation of heavy metals within the soil and sediments surrounding a copper mine in Kerman, Iran, yielded similar results, showing that heavy metal concentrations

declined as the distance from the mining site increased [154]. This pattern highlights the environmental impact of mining activities and the potential for natural attenuation over a distance [154].

In contrast to these findings, a critical study examining the impact of distance on metal pollution in sediment from a river system influenced by mining in Malaysia revealed a counterintuitive trend [155]. It was observed that concentrations of cobalt and manganese increased as the distance from the mining source grew [155]. This unexpected result is attributed to the higher solubility of these minerals in the aquatic environment and a lower metal partition coefficient, which complicates the relationship between distance and metal concentration in specific hydrological contexts [155].

2.5 Health Risk Assessment (HRA) of Heavy Metal Exposure

2.5.1 The United States Environmental Protection Agency (USEPA) Frameworks for Health Risk Assessment

Human health risk assessment estimates the possible and probability of adverse health implications resulting from exposure to chemicals in contaminated abiotic components of the natural environment, whether that exposure is ongoing or anticipated in the future [156].

The human health risk assessment process consists of five steps [156] :

- **Planning:** This step includes both the planning and scoping phases. During this time, the risk manager, risk assessor, and key stakeholders engage in discussions to identify objectives and explore risk management options. They assess relevant natural resources, define the scope and complexity of the assessment, and clarify the responsibilities of each team member.
- **Hazard Identification:** In this phase, the risk assessor determines whether a specific stressor poses a potential threat to humans or ecological systems. They also specify the conditions under which this threat may arise.
- **Dose-Response Evaluation:** The risk assessor collects data to establish the quantitative relationship between exposure levels and health outcomes.
- **Exposure Assessment:** The risk assessor reviews existing information regarding the timing, frequency, and intensity of contact with the stressor.
- **Risk Characterization:** This step includes two primary elements: risk estimation and risk description.

The risk estimation evaluates exposure levels for each stressor while considering relevant populations of plants, animals, communities, and ecosystems. It also includes data on the expected impacts for each group at those exposure levels [156].

The risk description provides insights into the expected outcomes of the risk assessment [156]. It details whether adverse effects are anticipated for the relevant plants and animals, offers qualitative comparisons, and considers the potential influence of uncertainties on the assessment [156].

Relevance of HRA for evaluating cancer risks in children

The World Health Organization (WHO) reports that nearly 400,000 young people and teens aged 0 to 19 are diagnosed with cancer worldwide each year[157]. In the United States, an estimated 14,910 new cases were expected among this demographic in 2024, Leading to about 1,590[158] deaths. Specifically, for children aged 0 to 14, 9,620 diagnoses were expected, with 1,040 fatalities; for adolescents aged 15 to 19, the projections indicate 5,290 diagnoses and 550 deaths[158].

Cancer risk in children and adolescents is influenced by genetic predispositions, early developmental genetic changes, and environmental factors such as exposure to toxins, heavy metals[159] and radiation[157 160]. The most prevalent types of paediatric cancers include acute lymphoblastic leukaemia (ALL), which affects the bone marrow and blood; brain tumours, which can vary widely in type and severity; lymphomas, including Hodgkin and non-Hodgkin lymphoma; and solid tumours such as neuroblastoma, which primarily occurs in infants and young children[157 161].

The above statistics reveal that children experience a higher prevalence of cancer and a greater cancer-related mortality rate compared to other age groups. This alarming reality highlights the pressing need for both preventive and therapeutic interventions targeted at children. In our specific study context, conducting a Health Risk Assessment (HRA) will be instrumental in estimating the risk levels associated with exposure to selected heavy metals for children aged 1 to 12 years in Kagiso. By thoroughly analysing these risks, the findings of this study will equip relevant authorities with critical data to make informed decisions and implement effective public health measures aimed at safeguarding the health of children in the Kagiso community.

2.5.2 Cancer Risks from Heavy Metal Exposure

The table 3 below offers a thorough overview of the significant sources of exposure to five heavy metals of concern. It outlines the carcinogenesis process associated with each metal and details the specific types of cancer linked to these hazardous substances. By examining these factors, we can better understand the possible health risks of heavy metal exposure and how they contribute to cancer development.

Table 3: Selected heavy metals sources, carcinogenesis and type of cancer caused

Heavy Metals	Main Source of exposure	Carcinogenesis	Type of cancer
Arsenic and its compounds.	Workers engaged in the use of Arsenic in vineyards, ceramics, glass production, smelting, refining, pesticides, wood preservation, and semiconductors [53 54 46].	Mutagenesis results from oxidative DNA damage, gene amplification, aneuploidy, genomic instability, and defective DNA repair [53 54 46].	Skin, lung, and urinary bladder cancers [53 54 46]
Cadmium and its associated compounds.	The metal industry and mining and battery production emissions are primary exposure sources. Cigarette smokers also have higher Cadmium levels than non-smokers [53 54 46].	Inhibition of DNA repair and dysfunction of tumor suppressor proteins, resulting in genomic instability [53 54 46]	Lung carcinoma [53 54 46].
Compounds of Chromium (VI).	Cr (IV) exposure in workers manufacturing cars, glass, pottery, and linoleum [535446].	Intracellular reduction to Cr(III) causes direct DNA damage, Leading to mutations, genomic instability, aneuploidy, and cellular damage transformation [53 54 46].	Lung carcinoma [53 54 46].
Compounds of Nickel.	Exposure mainly occurs through mining, smelting, and welding via inhalation and skin contact. The public faces low Nickel levels in air, water, food, and tobacco smoke from natural sources, industrial activities, and Nickel-plated items like coins and cookware [56 46].	Damage to DNA, chromosomal irregularities, genomic instability, micronuclei formation, impairment of DNA repair mechanisms, changes in DNA methylation, and histone modifications [56 46].	The nasal cavity, paranasal sinuses, and lung carcinoma [56 46]
Lead compound	Lead emissions mainly come from metal plating, mining, paints, cosmetics, batteries, electronic waste, and fossil fuel combustion [46 55].	Cancer pathophysiology occurs through three stages: 1. DNA mutations stimulate oncogenes and disable tumor suppressor genes. 2. The proliferation of mutated cells Leads to the formation of clusters. 3. Tumors invade nearby tissues and may spread via the bloodstream or lymphatic system [46 55].	Cancers of the esophagus, stomach, brain, kidneys, thyroid, and testes [46 55].

Thresholds and benchmarks for cancer risk assessment

Different regulatory bodies worldwide set specific thresholds for acceptable cancer risk, reflecting their unique approaches to public health and safety [162]. The U.S. Environmental Protection Agency (EPA) outlines its cancer risk threshold in the Integrated Risk Information

System (IRIS) Database, which is established at 10^{-6} [162]. This means that for every one million individuals exposed to a particular substance, one additional case of cancer might be expected to occur over a lifetime [162].

In contrast, Health Canada recommends a Maximum Acceptable Concentration (MAC) that is significantly higher, at 10^{-5}, indicating a greater tolerance for potential risk in specific contaminants [162] [163]. This standard serves as a guideline for evaluating drinking water safety and other environmental exposures [162].

Additionally, the U.S. EPA's Regions 3 and 6 have set a non-enforceable screening level for tap water at 10^{-5}, which is intended to help evaluate potential risks from contaminants before they necessitate regulatory action [164].

In California, the Public Health Goal for drinking water quality aligns with the more conservative threshold established by the IRIS Database, also set at 10^{-6} [162]. This reflects the state's commitment to minimizing cancer risk for its residents [162].

On a global scale, the World Health Organization (WHO) has established a guideline for cancer risk with a value of 10^{-5}, highlighting a relatively similar standard to that of Health Canada and the U.S. EPA screening level [162]. Such guidelines play a vital role in public health policy and help inform governmental regulations and community awareness efforts related to environmental health risks [162].

2.5.3 Case Studies on HRA Applications

Numerous studies within the mining industry have employed the US EPA HRA framework, including the following significant contributions:

An extensive evaluation of four studies examining health risks linked to toxic elements from mining industries across various global regions emphasized their effects on local communities [165] [166] [167] [168]. Most of these studies mainly utilized the United States Environmental Protection Agency (USEPA) health risk assessment model, while also integrating other methods like Redundancy Analysis (RDA), Unmix analysis, and Monte Carlo simulations to strengthen their conclusions [165] [166] [167] [168].

The findings consistently showed that mining activities were major contributors to environmental pollution, comparable to industrial emissions and vehicle traffic as key sources of toxic exposure [165] [166] [167] [168]. Alarmingly, these studies pointed out that children are the most

at-risk group, facing a significantly higher likelihood of developing cancer from exposure to these pollutants [165] [166] [167] [168]. This highlights the urgent need for targeted interventions and stricter regulations to reduce health risks linked to mining operations and protect vulnerable populations in affected regions.

2.6 Knowledge Gaps and Research Justification

Numerous comprehensive research studies conducted[29] [30] in South African communities situated near mining activities have revealed concerning levels of pollution by heavy metals across various environmental components, including soil, water, air, and sediments[63] [120]. These findings demonstrate a direct link between pollution levels and the operations associated with mining, industrial processes, and mining waste management. Notably, many of these studies indicate that contamination levels frequently exceed local regulatory limits and international health standards, indicating the pressing necessity for proactive procedures to protect public health.

The limited research on heavy metal pollution in the Kagiso area highlights a significant gap in our understanding of this issue, indicating a pressing need for further exploration. Children exhibit notable vulnerability to exposure due to their changing bodily functions and behavioural patterns, such as increased hand-to-mouth activity, which can elevate their risk of heavy metal ingestion. This vulnerability shows the importance of targeted health studies focused on paediatric populations and community awareness initiatives to educate families about the potential dangers associated with mining pollution.

Moreover, there is a notable deficiency in evaluations of existing government regulations, particularly concerning the effectiveness of buffer zones [36] [37] (38) designed to protect residential communities from the harmful impacts of mining-related pollution. This gap presents a critical opportunity for policymakers to enhance current strategies through rigorous regulatory assessment and implementation of evidence-based policies. Key stakeholders, including local governments, health organizations, and mining companies, can collaborate to develop effective strategies that improve public health and safety in affected regions by prioritising research, engaging in thorough evaluations, and fostering meaningful community involvement.

Additionally, more extensive investigations are essential to understand the long-term health effects of heavy metal exposure in children living in mining zones. Research should also focus on the bioaccumulation of heavy metals in the food chain, mainly through the consumption of

locally sourced foods, and seek to identify effective methods for reducing pollution exposure within these vulnerable communities. By deepening our understanding of these critical issues, we can work toward creating a safer and healthier environment for all residents living near mining activities.

Table 4 provides a comprehensive overview of selected heavy metals. It details the various routes through which these metals can enter the body, as well as their immediate and long-term effects on human health**.** This table serves as a crucial resource for understanding the potential dangers associated with exposure to these toxic substances.

Table 4: Heavy metal of concern, route of entry, immediate and long-term effects

Heavy Metal	**How It Enters the Body**	**Immediate Effects**	**Long-Term Effects**
Arsenic	Breathing, eating, drinking	Vomiting, seizures, death	Cancer, kidney disease
Cadmium	Breathing, eating	Lung damage, organ failure	Bone diseases, cancer
Chromium VI	Skin, air, food	Organ failure, asthma	Lung cancer, skin disease
Lead	Air, food, water, skin	Stomach pain, kidney damage	Brain damage, heart disease
Nickel	Skin, air, food	Breathing problems, vomiting	Lung cancer, skin allergies

Who Is at Risk?

- **Children** (1-12 years) are most vulnerable because they:
    - Eat, drink, and breathe more than adults (relative to body size).
    - Put hands and objects in their mouths.
    - Have weaker detox systems.
- **People near mining areas** (especially **within 5 km of waste sites**) face **higher exposure risks**.

How Heavy Metals Spread

- **Air**: Factories and mines release particles that **travel up to 20 km**.
- **Water**: Rain washes pollutants into rivers and groundwater.
- **Soil**: Contaminated dust, fertilizers, and waste get absorbed by plants and animals.
- **Food chain**: Metals build up in plants, animals, and humans.

Cancer Risks from Heavy Metals

Prolonged exposure to heavy metals can increase cancer risk by damaging DNA. Below is a table summarizing the types of cancer linked to long-term exposure to specific heavy metals.

Table 5: Heavy metal of concerns with main exposure source and cancer type

Heavy Metal	Main Exposure Sources	Cancer Type
Arsenic	Pesticides, smelting, wood preservation	Skin, lung, bladder
Cadmium	Mining, batteries, smoking	Lung cancer
Chromium VI	Car manufacturing, glass & pottery	Lung cancer
Nickel	Mining, smelting, welding	Lung, nasal cancer
Lead	Batteries, fuels, mining	Brain, stomach, kidney cancers

Experts use **risk assessment models** to estimate health dangers from pollution. Studies confirm:

- Children are at the highest risk.
- Cancer risks are much higher in mining areas.
- Toxic metals travel long distances, affecting communities far from mines.

CHAPTER 3: METHODOLOGY

This section provides a detailed overview of the research methodologies employed in the study, including the structured study design and the specific criteria for selecting locations aligned with the study's objectives. It describes the systematic techniques used for sample collection, emphasising their importance and rigour in acquiring relevant data. The section also outlines the detailed steps involved in data analysis, focusing on the analytical tools and frameworks that help maintain the integrity of the results. Ethical considerations are carefully addressed. Lastly, it discusses the quality assurance measures put in place to ensure the reliability and validity of the findings.

3.1 Study Design:

The researcher utilized a cross-sectional study design for this investigation, leveraging its numerous advantages. This approach is particularly effective for simultaneously assessing a wide range of outcomes and risk factors, significantly broadening the scope of data collected. [169]. Its cost-effectiveness and effectiveness in terms of time make it an appealing choice for research, allowing for comprehensive data collection within a relatively short time frame. [169].

Furthermore, the cross-sectional nature of this study facilitates the identification of potential associations among various variables, yielding valuable insights into their interrelationships. [169]. These results enhance our comprehension of the subject matter and provide a solid foundation for guiding future research efforts and informing public health interventions to address the identified issues [169].

3.2 Study Setting:

The research was conducted in Kagiso (coordinates 26°8'S 27°47'E), a township in Gauteng Province (as shown in figure 1), South Africa, under the Municipality of Mogale City in the West Rand District[170]. As of 2019, the population of West Rand was approximately 889,731; most residents were in the working age range, with the mining and agricultural industries accounting for most economic activity [171]. In 2018, 46.58% of the population was employed, and 61% of residents lived in formal housing, which refers to legally recognised housing that meets specific standards [171].

Kagiso has a population of 115,802 people living in 35,098 households throughout a 14.17 km2 area. Of the population, 25% are aged 0–14 years, while 71.9% are between 15 and 64 years [172]. The homes in Kagiso are located next to an abandoned mine tailing storage facility

(*Figures 2& 3*). Soil samples were taken from different parts of Kagiso, such as mine tailing storage facility, communities, primary schools, soccer fields and day-care facilities. In Kagiso, preschools were found within primary schools. No park was seen around, only sports facilities used as parks and playgrounds.

A recent study [39] indicates that Kagiso is located on mine tailings from previous mining operations, which are known for their rich geological composition and valuable mineral deposits. Among these minerals are pyrite, commonly called "fool's gold," and arsenopyrite [173] (FeAsS), a source of Arsenic [39]. Cobaltite (CoAsS) [174] serves as an important source of cobalt, while brannerite ($UO_3Ti_2O_4$) [175] provides uranium. The site also contains chromite ($FeCr_2O_4$) [176], essential for Chromium production, as well as galena (PbS) [177], the primary ore for Lead [39].

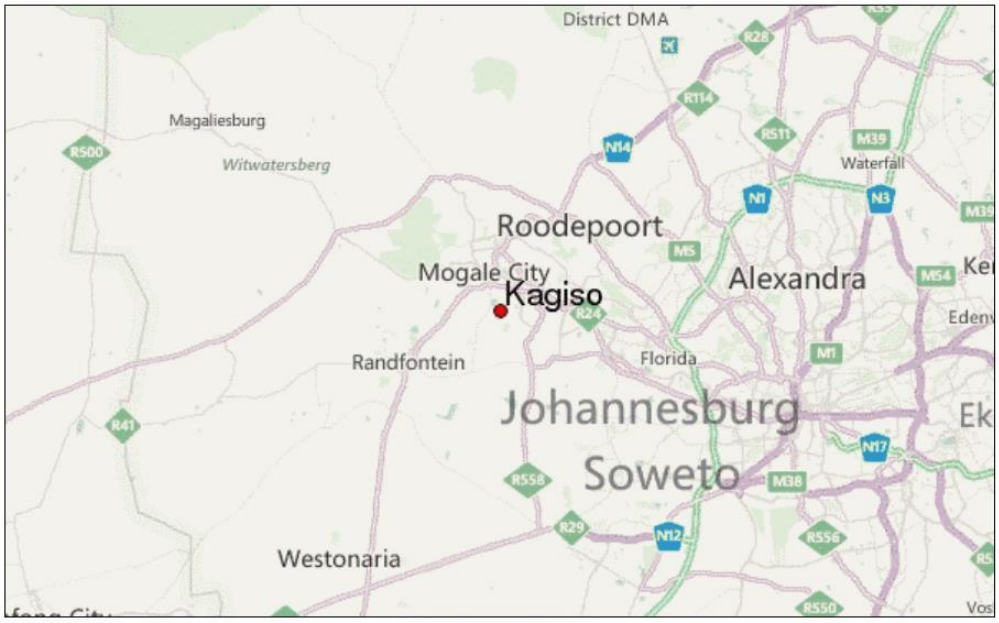


Figure 1 : A map showing the location of Kagiso township [178]

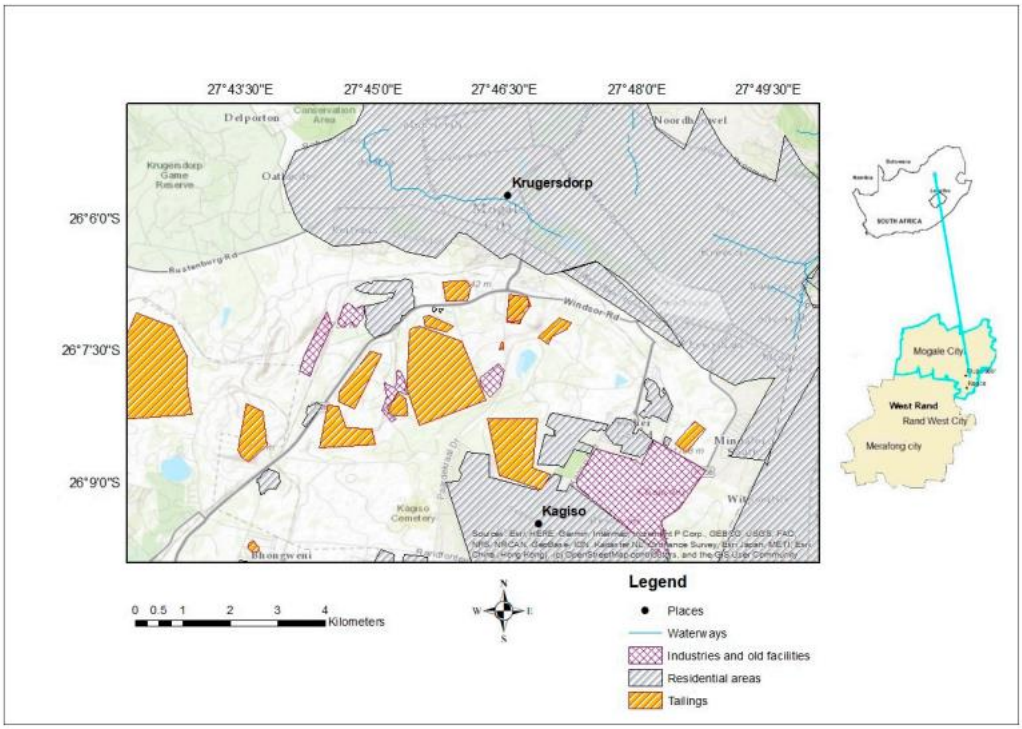


Figure 2: Location of Kagiso with industries and old facilities, with residential areas and tailings [179]



Figure 3: Kagiso community with tailing storage facility in the background (Photo credit : Jacques Tshunza)

3.3 Sample collection:

Soil samples for analysis of selected heavy (As, Cr, Cd, Ni, and Pb) metals due to their carcinogenic risk[27] [46] [48] [55] were collected from various strategic locations in Kagiso. The researchers used a random selection method to choose sites likely to have children, such as schools, day-cares, playgrounds, and community yards. Samples were also collected from the community clinic.

The collection process began at the tailing storage facility (see *Figure 4*), which was assumed to be a potential source of contamination, and then moved towards the surrounding community. Collaborating with a field worker and a specialist in the field, the researcher used shovels to gather topsoil samples, each weighing approximately 400 grams (99). The top layer of the ground was removed before collecting samples, which were placed in polypropylene bags. The samples were collected at an average depth of 15 to 20 centimetres to ensure representativeness, resulting in a sample from each site.



Figure 4: Research team, while collecting samples (Photo credit: Jacques Tshunza)

Soil samples were gathered in a zigzag pattern, moving diagonally across the site with alternating directions and sampling at irregular intervals throughout the collection area in Kagiso to reduce variability in the sampled areas and enhance data reliability across the terrain. [180]. Two soil samples were obtained from each designated location, except the community clinic, where only one was collected due to its limited size of less than 4 hectares. [181].

The sampling continued from the tailing storage facility into the community (Table 6). After collection, the composite samples were securely stored in polypropylene bags, sieved to remove larger particles, and transported to the laboratory under controlled conditions to preserve sample integrity.

The researcher repeated the sample collection process at the tailing storage facility to validate the initial findings. Additionally, we took extra samples from an excavation site where children were observed playing, which raised significant concerns about their potential exposure to hazardous substances. To further our investigation, we also collected samples at the primary school to confirm the previously identified elevated levels of heavy metals in the soil.

The distances between the sample collection points varied considerably: from 200 to 300 meters in the community, 150 meters at the primary school, 45 meters at the soccer field, and 300 meters at the adjacent day-care. This meticulous approach was designed to capture the spatial variability of soil contamination across the area, providing a detailed assessment of the community's environmental health risks linked to heavy metal exposure.

The total number of samples collected were 14, each contributing valuable insights to our ongoing investigation into the safety and well-being of residents, particularly the children who frequent these areas.

A global positioning system (GPS) was employed to accurately document the sampling points' locations. This advanced technology ensured that each collection site could be identified accurately. Below is a detailed list of the various sampling locations, along with their corresponding latitude and longitude coordinates for easy reference and verification:

Table 6 provides a detailed overview of the various collection sites. It includes information on the frequency of collection cycles, the distances from each collection site to the tailings storage facility (TSF), and the precise geographical coordinates for each location. This comprehensive data will facilitate a better understanding of the logistics involved in the collection process and its proximity to the TSF.

Table 6: Collection sites categorized by their distance from the tailing storage facility and coordinates

Collection Cycle	Collection sites	Distance in meters from the TSF, measured as a radius	Coordinates
1st cycle	Mine tailing storage facility (TSF) 1	10	-26.197809, 27.785248
	Mine tailing storage facility 2	20	-26.198186, 27.785812
	Community 1	100	-26.197882, 27.786169
	Community 2	200	-26.195916, 27.789116
	Primary School 1	110	-26.195255, 27.785449
	Primary School 2	200	-26.193859, 27.785066
	Soccer Field 1	150	-26.196043, 27.785103
	Soccer Field 2	200	-26.195504, 27.784750
	Community Clinic	1000	-26.194661, 27.789101
	Day-care 1	1100	-26.195431, 27.792512
	Day-care 2	1500	-26.194498, 27.793299
2nd Cycle	Mine tailing	0	-26.197809, 27.785248
	Primary School	200	-26.193859, 27.785066
	Excavation land	380	-26.192957, 27.780924

Following collection, all soil samples were meticulously labelled and packaged to prevent contamination. They were then dispatched to a reputable[182] independent laboratory (The Environmental Geochemistry Laboratory of the University of the Witwatersrand, Johannesburg) with accreditation under the South African National Standards (SANS) 17025.

3.4 Sample analysis

Microwave-Assisted Digestion technique was used for laboratory analysis of soil samples.

Equipment used: The CEM MARS 5 microwave and the Multiwave 3000 digestion (Manufacturer: Spectro, Model: Genesis).

The following experimental steps were taken:

Reagents used:

- HNO_3 (Nitric Acid) 65%
- HCl (Hydrochloric Acid) 32 %
- HF (Hydrofluoric Acid) 48 %

Procedure followed:

- Sample Preparation: Accurately weigh 0.25 g of soil and transfer it into a microwave digestion vessel.
- Adding Reagents: Carefully introduce 18 mL of HNO_3, 6 mL of HCl, and 2 mL of HF into the vessel. Exercise caution, as the mixture will generate heat and fumes.
- Sealing and Digesting: Secure the vessel tightly and place it in a microwave digestion system set to 200°C to break down the soil efficiently. The digestion takes 50 minutes (15minutes ramp to 150 °C then 5 minutes to 200 °C then hold for 30 minutes at 200 °C)
- Cooling: After digestion, allow the vessel to cool to room temperature before proceeding.
- Filtration and Dilution: Filter the digested solution to remove any solid residues, yielding a clear solution suitable for analysis. Dilute as needed to ensure accurate quantification of the elements. The dilution depended on the calibration range and the initial concentration of heavy metal detected.
- The chemical analysis of heavy metals was done by the ICP-OES, Spectro Genesis.

3.5 Data Management:

The laboratory analysis report's measurements were meticulously transferred to an Excel spreadsheet, ensuring accuracy in data handling. The information was securely shared with the supervisor via password-protected emails to maintain confidentiality. To visualize the data more effectively, we chose to utilize Google Earth rather than the conventional Google Geographic Information System (GIS). This allowed us to map the collection sites in Kagiso vividly, clearly indicating the heavy metal that exhibited the highest concentration among all the heavy metals analysed.

3.6. Data Analysis:

Stata 18.0 was utilized as the statistical software for conducting the analysis. The results obtained from the soil samples were rigorously assessed against established benchmarks set by South Africa’s regulatory standards, as well as international guidelines provided by the Food and Agriculture Organization of the United Nations (FAO), the European Union (EU), and the World Health Organization (WHO). This comprehensive comparison ensured that the soil quality was evaluated within recognized health and safety parameters, contributing to a thorough understanding of its environmental impacts.

To ensure robust data interpretation, a thorough descriptive analysis was conducted. This analysis involved identifying suitable measures of central tendency, such as mean, median, and mode, and assessing measures of dispersion, including range, variance, and standard deviation. Furthermore, inferential statistics were applied to draw conclusions from the sample data. In contrast, careful consideration of the data's skewness was considered to ascertain whether the distribution followed a normal pattern or exhibited skewness, which could affect the validity of the statistical analyses.

The study evaluates the health risks of exposure to heavy metals (Lead, Chromium, Cadmium, Nickel, and Arsenic) in soils near mine dumps in Kagiso, South Africa. One of the primary objectives is to analyse the connection between heavy metal concentrations and the distance from the mine dumps. To achieve this, we needed to select a statistical method appropriate for the characteristics of the collected data.

3.6.1. Wilcoxon rank-sum test and the Kruskal-Wallis test

Due to the limitations associated with Pearson's test, the researcher chose to employ non-parametric tests, specifically the Wilcoxon rank-sum and Kruskal-Wallis tests. This decision was driven by the robustness [183] of these tests to depart from normality, as non-parametric methods do not require the data to adhere to a normal distribution. This is especially relevant given the skewness and high variability present in the dataset.

Moreover, non-parametric tests exhibit insensitivity [184] to outliers, which enhances their reliability in cases where certain sites may display unusually high concentrations. They are also capable of capturing non-linear relationships, facilitating the discovery of complex patterns [185] crucial for understanding the distribution of heavy metals in the environment. Additionally, these methods perform well even with small sample sizes [186], making them particularly appropriate for the context of our study.

3.6.2. Relationship between heavy metal concentration and distance from the TSF (objective 2):

Kruskal-Wallis test

Given the substantial skewness in our data set, we concluded that non-parametric tests, specifically the Kruskal-Wallis and Mann-Whitney U tests, were more suitable for our analysis than a nonlinear regression model. This choice was driven by the need to accurately evaluate

the association between heavy metal concentrations and the varying distances from the tailing storage facility. Non-parametric tests are particularly beneficial in this context, as they do not rely on the assumption of a normal distribution of the data, enabling a more robust assessment of how proximity to the storage site influences heavy metal levels. By utilizing these tests, we sought to better understand the potential environmental impact of tailings on local ecosystems. [187] [188]. To perform both tests; the Kruskal-Wallis and Mann-Whitney U tests we categorized the distances in zones near (0 -100 meter), mid (101 – 500 meter), far (> 500 meter) and the heavy metal concentrations as distinct group.

Research Hypothesis

Null hypothesis: There is no association between heavy metal levels and the distance from the tailing dump.

Alternative hypothesis: There is an association between heavy metal concentration and the distance from the tailing dump.

The same hypothesis was utilized for the Kruskal-Wallis and Wilcoxon rank-sum tests.

A Kruskal-Wallis test was conducted to determine if there were statistically significant differences in metal concentrations across various collection sites for Arsenic (As), Nickel (Ni), Cadmium (Cd), Chromium (Cr), and Lead (Pb).

3.6.3 Deterministic Health Risk Assessment Methodology (objective 3):

Since the contaminants are carcinogenic with toxicity expressed as lifetime, the lifetime average daily dose (LADD) was calculated as suggested by United States Environmental Protection guidelines [189] using Equation 1.

$$LADD_{soil} + dust_{ing} = \frac{C_{soil+\ dust} \times CF \times IR_{soil\ +\ dust} \times EF \times ED}{BW \times LT} \qquad \text{Equation 1}$$

Where LADD $_{\text{soil + dust ing}}$ refers to the potential lifetime average daily dose from ingestion of soil and dust (mg/kg-d), $C_{\text{soil + dust}}$ is the concentration of contaminants in soil and dust (mg/g). For the worst-case scenario, the researcher has used the highest concentration of each selected heavy metal in the community [190] [191]. CF is the conversion factor of 0.001 g/mg; IR soil + dust is the intake rate of soil and dust (mg/d) - a central tendency intake rate of soil and dust in

United States Environmental Protection Agency (US-EPA) 2017 was used (see Appendix C for reference values) [191].

EF is the exposure frequency (d/yr). For children from 1 to below 6 years, exposure frequency for residential exposure is 350 days per year since they spend about 2 weeks away from home, with home considered as the primary source of exposure [189]. The researcher has extended this duration up to below 12 years to assess the worst-case scenario [190].

For preschool children, the average number of days spent at school is 195 per year in South Africa [192] [193] [194].

For children of 6 years and above, the South African School calendar was used to estimate the time children spend at and out of school [195] (see Appendix D for reference values) to assess exposures from different microenvironments; ED is the exposure duration (yr); BW is the average body weight (kg); and LT is lifetime expectancy (d/ yr) and equivalent to 63.6 years for males and 66.5 years for females [196].

LT: Recommended for carcinogenic substances is 70 years[189].

BW: I have used the South African children's weight from a 2008 study from the University of Cape Town (see Appendix E for reference values) [197] to estimate the mean weight for predefined age groups presented in the above lines.

Concerning the exposure duration (ED), in this study, the researcher considered children from 1 to 12 years based on available South African children's standard weight, who were then divided into four age groups as follows: the researcher considered children from 1 to 12 years who were allocated to four age groups as follows: 1 to < 2, 2 to < 6, 6 to < 12, and 12 years [191]. To distinguish between day-care and primary school ages, the researcher took into account the childcare age range of 1 to under 6 years [198] [199] and 6 to 12 years for primary school [200].

The cancer risk related to each heavy metal was estimated by multiplying the LADD by the respective heavy metal slope factor [201] using Equation 2.

$$\text{Cancer Risk (CR)} = \text{LADD} \times \text{SF} \qquad \text{Equation 2}$$

Where SF is the slope factor for the carcinogenic contaminants (see Appendix B for reference values) [201] [202].

The table below offers a thorough collection of conversion factors for different heavy metals. These vital tools assist in accurately calculating the lifetime average daily dose for each metal, enhancing our comprehension of potential exposure levels. By presenting this information, the table is crucial for evaluating health risks linked to these heavy metals, emphasizing their importance in protecting public health and guiding risk management strategies.

Table 7: Parameters used for the Lifetime Average Daily Dose (LADD) and Cancer Risk in Children from 1 to 12 years

Parameters used to calculate the Lifetime Average Daily Dose values and Cancer Risk in children	
Parameters	**Unit**
The concentration of contaminants in the soil as $C_{soil+dust}$	mg/g
Ingestion Rate $_{soil+dust}$ as IR $_{soil+dust}$	mg/day: 90 for 1 to < 2 years, 60 for 2 to < 6 years and 6 to < 12, and 30 for 12 years [191]
Mean ages as ED	years: 1 for 1 to < 2 years, 3.5 for 2 to< 6 years, 8.5 for 6 to < 12, and 12 years for 12[191] [195]
Mean weight as BW	Kg: 10.8 for 1 to < 2 years, 15.625 for 2 to< 6 years, 27.75 for 6 to < 12, and 39.3 for 12 [197]
Exposure frequency in the community as EF	d/yr: 365 for 1 to < 2 years, 170 for 2 to< 6 years, 160 for 6 to < 12, and 160 for 12[195]
Exposure frequency at the primary school as EF	d/yr: 205 for 6 to < 12 years, and 205 for 12 years[195]
Exposure frequency at the day-care as EF	d/yr: 195 for 2 to< 6 years, [192] [193] [194] [195]

According to the US EPA, a cancer risk of $1x10^{-6}$ and below is typically considered an acceptable risk threshold for regulatory purposes, risks between $1x10^{-6}$ and $1x10^{-4}$ fall into the risk management range, and risk greater than $1x10^{-4}$ are considered unacceptable [203].

3.7 Quality Assurance Measures:

Zigzag sampling represents an effective methodology for achieving optimal coverage of an area through a systematic navigation of the terrain. [180]. This approach ensures that each zone is

adequately represented, facilitating a thorough and balanced evaluation of the environmental conditions. [180]. By methodically traversing the landscape in a zigzag pattern, this technique captures the diverse characteristics of the ecosystem, ensuring that critical aspects are not overlooked. [180]. Consequently, this method enhances the quality of the data collected and fosters a comprehensive understanding of the intricate dynamics within the studied environment. [180].

The soil samples were systematically collected and subsequently submitted for analysis to an independent laboratory accredited under South African National Standards (SANS) 17025. The laboratory conducted a comprehensive assessment to quantify the levels of heavy metals present in the samples, thereby ensuring a precise evaluation of soil contamination risks.

The following quality assurance measures were also implemented at the laboratory:

- Calibration was performed using standards at multiple concentrations (calibration curve) before sample analysis.
- A calibration blank was used to check for baseline contamination or instrument noise.
- An internal standard was added to each sample and standard to correct for matrix effects and instrumental variations.
- Two quality control samples (with known concentrations, low and high) were run at regular intervals during the analysis to monitor instrument performance.
- Duplicate samples were analysed to assess the precision of the results.
- Reagent blanks were analysed to monitor for any contamination introduced during sample preparation.
- Instrument blanks were run between samples to check for carryover or memory effects.
- Clean labware and high-purity reagents were used to minimize contamination.
- The matrix of calibration standards was matched to that of the samples to reduce matrix effects.
- The stability of the plasma was monitored by the flow of Argon to ensure consistent instrument performance.

3.8 Ethical Consideration:

Before sample collection, an ethics waiver was obtained from the Human Research Ethics Committee at the University of the Witwatersrand Johannesburg. The current research's ethics application study reference number is W-PR-231129-02 (See Appendix F). The researcher secured approval from the relevant facility management before initiating the sample collection

process. This step ensured compliance with informed consent, fairness, accountability and maintained the integrity of the research.

CHAPTER 4: RESULTS AND DISCUSSION

This chapter delves into the findings of a comprehensive health risk assessment focused on children aged 1 to 12 years residing in Kagiso, West Rand, who have been exposed to soils contaminated with hazardous heavy metals, including Arsenic, Chromium, Cadmium, Nickel, and Lead. It meticulously outlines the varying concentrations of these toxic elements across different locations within the community, highlighting the concerning relationship between the proximity to mining waste and the elevated levels of these metals in surrounding areas.

Furthermore, the chapter explores the estimated cancer risk associated with exposure for distinct age groups, providing critical insights into the vulnerabilities faced by young children. To contextualize these findings, a thorough comparison is made with results from other relevant research studies, enriching our understanding of the potential health implications associated with environmental contamination in this region.

4.1 Heavy metal emission factors.

The analysis delved into the concentrations of several heavy metals, namely Arsenic (As), Cadmium (Cd), Nickel (Ni), Chromium (Cr), and Lead (Pb), across a range of sites in Kagiso, South Africa. These sampling locations encompassed diverse environments, including areas adjacent to industrial facilities, densely populated residential neighbourhoods, and extensive tailings storage facilities. Table 9 shows median values, interquartile ranges, and skewness for each metal, highlighting the considerable spatial variability and the complexity of contamination levels across different locales.

Table 8: Combined table of Maximal Allowable limit of Concentration of Heavy Metals Soil (mg/kg) FAO/WHO,EU, and South Africa with Average Concentration (mg/kg) of Heavy Metals in Different Locations

Maximum Allowable Limit of Concentrations of Heavy Metals in Soil (mg.kg-1) FAO/WHO, EU, and South Africa						
		As	**Cd**	**Cr**	**Ni**	**Pb**
FAO/WHO Guidelines		20	3	100	50	100
EU Guidelines		n.a	3	150	75	300
South Africa		5.8	7.5	6.5	91	20
Collection Site	**Distance from the TSF in meters**	**Average Concentrations (mg/kg) of Heavy Metals in Different Locations**				
		As	**Cd**	**Cr**	**Ni**	**Pb**
Mine Tailings Storage Facility 1	0	43.50**	10.29**	324.00**	0	27.1
Mine Tailings Storage Facility 2	10	123.35**	11.06**	321.20**	0	60.08*
Mine Tailings Storage Facility 3	20	38.89**	11.60**	170.50**	0	0
Community 1	100	5.18	7.99**	254.40**	0	0
Community 2	200	7.96**	10.32**	395.10**	42.25	0
Primary School 1	110	0	8.63**	169.45**	0	0
Primary School 2	200	0	7.79**	192.70**	0	0
Soccer Field 1	150	0	6.19**	169.40**	0	0
Soccer Field 2	200	15.33**	13.20**	236.43**	18.73	15.2
Excavation land	300	52.50**	23.60**	227.80**	67.20*[w]	15.75
Community Clinic	1000	0	9.63**	375.90**	21.63	0
Daycare 1	1100	0	10.30**	271.40**	0	0
Daycare 2	1500	0	7.29**	243.80**	0	0
Median		**5.18**	**10.29**	**243.8**	**0**	**0**
IQR		**38.89**	**3.07**	**128.5**	**18.73**	**15.2**
Skewness		**1.91**	**2.15**	**0.47**	**1.72**	**2.08**
** Values above the EU and FAO/ WHO guidelines and the South African national standards						
*[s] Levels are above the South African national standards only but below the EU and FAO/WHO guidelines						
*[w] Levels are above the FAO/Guidelines only but are below the EU guidelines and SA national standards						

Results indicate that the levels of heavy metals were above maximal allowable limits at most of the sampled sites. For example, Arsenic (As) levels were above maximal allowable limits at the TSF but lower at community 1, the primary school and the soccer field 1 (Table 7). The concentrations of Arsenic at the Tailings Storage Facility (TSF) alarmingly surpassed the established limits set by South African (SA) regulations and those recommended by the FAO/WHO. Interestingly, as one moves away from this contaminated site, levels of Arsenic drop notably, particularly in areas situated 100 meters away, where they hover close to SA thresholds. The lowest Arsenic concentrations were identified in other zones such as the primary school, the soccer field (150 m from the TSF), the community clinic, and the day-care centre (1000-1500 m away). However, the excavation site (300 m) presented a stark contrast, recording Arsenic levels that exceeded all reference limits.

Cd and Cr were above the permissible levels in all sampled sites, with significantly higher concentrations at the community clinic than at the Tailings Storage Facility (TSF) (Table 7). High levels of Cadmium were recorded, with most surveyed areas surpassing the permissible limits from SA, FAO/WHO, and EU standards. The only exception was found in select sections of the soccer field (150 m), where Cadmium levels dipped below SA standards but remained higher than the FAO/WHO and EU thresholds. The most alarming Cadmium concentration was detected at the excavation site (300 m from the TSF). Similarly, Chromium levels exceeded all three reference values in most locations. Notably, the highest concentrations emerged in the community area (200 m from the TSF) and at the community clinic (1000 m from the TSF), signalling potential exposure for residents frequenting these sites.

Ni was high at the excavation site, high above the WHO guidelines but lower than the SA national standards and the EU guidelines. The concentrations were generally within acceptable limits, except at the excavation site (300 m), where they crossed the EU limit while still aligning with SA and FAO/WHO standards. Similarly, Pb was highest, about 100 meters from the TSF, but remained below the FAO/WHO and EU limits in all sample sites, yet unexpectedly exceeded SA limits exclusively at the TSF.

Several potential factors may have contributed to elevated heavy metal levels in all the sampled sites. First, soil pH levels within the Kagiso community was found in a study to be lower (between 2.69 and 5.09)[204]. Low pH can enhance the solubility and bioavailability of the metal in the environment, making it more accessible to both biological organisms and humans. Research has demonstrated that increased pH levels could reduce the mobility of heavy metals

in soil, consequently Leading to higher concentrations in specific areas [122] [123] [124] [125] [126] [127] [128] [129].

This suggests that the local chemical dynamics, including soil composition and pH, might play a pivotal role in influencing the behaviour and concentration of heavy metals.

Another critical factor to consider is the impact of precipitation and atmospheric deposition in the Kagiso region. These environmental processes may facilitate the runoff of contaminants from the Tailings Storage Facility, allowing harmful substances, including Arsenic, Chromium and Cadmium, to infiltrate neighbouring communities. Furthermore, atmospheric deposition, where pollutants settle from the air, could exacerbate the concentration of Chromium in residential areas. Other studies indicated that both precipitation and atmospheric deposition are significant contributors to the accumulation of heavy metals, creating serious health risks for the local population [135] [136] [137] [138] [139].As a result, residents may face heightened exposure to these hazardous substances.

Additionally, the unique geological characteristics of the Kagiso region [39] may play a substantial role in the observed Chromium levels and Lead [39] [175] [177]. The area's specific soil composition and mineral content could interact with industrial processes, especially if non-ferrous industries are nearby. These industrial activities may contribute to releasing Chromium and other heavy metals into the local environment. A recent study suggests that such interactions between local geology and industrial operations could Lead to increased concentrations of heavy metals [123] [132] [133] [134]. This warrants further investigation [130] Grasping these intricate associations is essential for formulating effective strategies to reduce contamination and safeguard the community's health.

The current study uncovered interesting parallels with other investigations carried out in industrial zones and the adjacent communities regarding the exposure to heavy metal levels that surpassed established reference limits. Notably, the research conducted by Kamunda and Mathuthu (2016)[47] in the Witwatersrand Gold Mining Basin found alarming levels of As (79.40 mg/kg), Cr (278.76 mg/kg), and Ni (112.06 mg/kg) in soil samples near gold mines, all exceeding accepted values and posed carcinogenic risks via ingestion. Lowanika and David that found in Kagiso high level of Cr (162.0 mg/kg) followed by Ni (136.0 mg /kg), As, Cd and Pb were not found in their samples [33].

In contrast, the current study's findings differed from an earlier investigation in the same region, which reported high levels of As, Pb, and Cd but no Cr, raising public health concerns[205]. This significant difference may be attributed to slope soil erosion [135] [136] [137] [138] [139], which plays a crucial role in the distribution and spread of heavy metal pollution in the environment.

4.2 The correlation between the distances from the mining dump and selected places in Kagiso.

The Kruskal-Wallis test was conducted to evaluate whether there were statistically significant differences in the concentrations of five metals: Pb, Cd, Ni, Cr, and As across various collection sites. The test results, detailed in Table 9, revealed relatively high p-values for all the metals analyzed: 0.6623 for Cd, 0.2631 for Cr, 0.2694 for Ni, and 0.3009 for Pb, with As showing a p-value of 0.0540. Since these p-values exceed the conventional significance threshold of 0.05, the findings suggest that there are no statistically significant differences in metal concentrations across most collection sites, except for As, which displayed a borderline result. This implies that the distribution of metals in the sampled locations is fairly uniform, with no specific site exhibiting extreme deviations from the tailings storage facility (TSF) to the site farthest from the TSF for Pb, Cd, Ni, and Cr. The results concerning As suggest potential variability in its levels across the near, mid, and far sites.

The Kruskal–Wallis test calculates a chi-square (χ^2) statistic, which measures how much the observed rank sums differ from what would be expected under the null hypothesis that all groups have equal distributions. A higher χ^2 value suggests greater differences in the median values among the groups. In this study, As produced the highest χ^2 value ($\chi^2 = 5.839$, $df = 2$), which corresponded to a borderline p-value ($p = 0.054$). This indicates a near-significant variation across different distance groups. In contrast, the χ^2 values for all other metals were small, leading to non-significant p-values, which implies that there were no meaningful differences between these groups.

Table 9: Summary of Kruskal-Wallis test results

Metal	χ^2 (no ties)	p (no ties)	χ^2 (with ties)	p (with ties)	Interpretation
As	5.277	0.0715	5.839	**0.0540**	Borderline difference across groups
Cd	0.824	0.6623	0.824	0.6623	Non-significant
Cr	2.670	0.2631	2.670	0.2631	Non-significant
Ni	1.758	0.4151	2.623	0.2694	Non-significant
Pb	1.610	0.4471	2.402	0.3009	Non-significant

Wilcoxon rank-sum tests in Table 10 revealed that Arsenic concentrations were the only significant difference between the groups, with sites near the tailings storage facility (TSF) exhibiting higher levels than those farther away ($p = 0.0277$). In contrast, no significant differences were observed for Cd, Cr, Ni, or Pb across any pairwise comparisons ($p > 0.10$). These results indicate that As contamination is localized to the vicinity of the TSF, while the distribution of the other metals appears to be more uniform across the study area.

These results align with the earlier Kruskal-Wallis test findings, reinforcing that As shows the strongest evidence of contamination related to distance, with significantly higher concentrations near the mine tailings compared to locations further away. Other metals, such as Cd, Cr, Ni, and Pb, did not exhibit statistically significant variations with distance.

Table 10: Summary of the Wilcoxon rank-sum test

Metal	Near vs Mid (p)	Near vs Far (p)	Mid vs Far (p)
As	0.1308 (Non-significant)	**0.0277**	0.1674 (Non-significant)
Cd	0.8312 (Non-significant)	0.2888 (Non-significant)	0.6056 (Non-significant)
Cr	0.2864 (Non-significant)	0.7237 (Non-significant)	0.1213 (Non-significant)
Ni	0.1155 (Non-significant)	0.2482 (Non-significant)	0.5716 (Non-significant)
Pb	0.3367 (Non-significant)	0.1859 (Non-significant)	0.2888 (Non-significant)

Our comprehensive analysis, utilizing P-values derived from both the Kruskal-Wallis test and the Wilcoxon Rank-Sum test, reveals no significant association between the concentration of Cd, Cr, Ni, and Pb and the distance from the tailing dump. This finding suggests that proximity to the mining site does not directly influence the environmental levels of Cd, Cr, Ni, and Pb. It could be caused by the small size of the studied area, which is susceptible to the influence of dust storms. As such, there is a need for source apportionment of metals in the community to determine enrichment factors and contamination factors.

Additionally, the presence of other potential sources of heavy metals in Kagiso, as demonstrated by different research [130] [145] [146] [147] [148] [149] [150], could contribute to fluctuations in their levels across different collection sites. These external factors may mask any potential association between Cd, Cr, Ni, and Pb levels and distance from the mine, highlighting the complexity of environmental contamination in urban settings.

4.3 Health risk assessment

The table below outlines several key parameters for estimating the average daily lifetime exposure to specific heavy metals. This comprehensive analysis aims to enhance our understanding of the systematic methods researchers use to evaluate the associated cancer risks. By considering factors such as exposure frequency, ingestion rate, age, weight, and the concentration of heavy metals in the soil, this study seeks to highlight the potential long-term health impacts of these metals.

Table 11 shows the estimated lifetime average daily dose (LADD) values for different age groups of children aged 1 to 12 years, highlighting their exposure levels to the heavy metals studied. This detailed breakdown provides a clearer understanding of how these values vary across different developmental stages, highlighting the potential impact of heavy metal exposure on children's health and wellbeing.

Table 11: The Estimated Lifetime Average Daily Dose (LADD)

	Lifetime average daily dose (LADD) values in mg/kg/day					
Location	Age group (yr)	As	Cd	Cr	Ni	Pb
Community 150 m	1 to < 2	7.82E-07	1.09E-06	3.87E-05	2.51E-06	0
	2 to < 6	5.88E-07	8.19E-07	2.90E-05	1.89E-06	0
	6 to < 12	7.56E-07	1.05E-06	3.74E-05	2.43E-06	0
	12	3.77E-07	5.25E-07	1.86E-05	1.21E-06	0
Primary school 155 m	6 to < 12	0	9.45E-07	2.08E-05	0	0
	12	0	4.71E-07	1.04E-05	0	0
Day care 1300 m	2 to < 6	0	7.86E-07	2.30E-05	0	0

The table 12 below offers a thorough collection of slope factors for selected heavy metals. These vital tools assist in accurately calculating the lifetime average daily dose for each metal, enhancing our comprehension of potential exposure levels. By presenting this information, the table is crucial for evaluating health risks linked to these heavy metals, emphasizing their importance in protecting public health and guiding risk management strategies.

Table 12: Slope Factor for Selected Heavy Metals[201 202]

Heavy metal	**Slope Factor (mg kg^{-1} $d^{-1})^{-1}$**
Cr	0.5
Cd	0.38
Pb	0.0085
Ni	1.7
As	1.5

Figure 5 illustrates that among the five carcinogenic heavy metals selected for analysis, only Chromium (Cr) exhibited a lifetime cancer risk exceeding the US Environmental Protection Agency (EPA) reference value of $1x10^{-6}$. Notably, the lifetime cancer risk for Cr was below the reference value only for 12-year-old children residing in the community and attending primary school. Cr was implicated as the most significant contributor to carcinogenic risk among the metals analysed, suggesting a need for focused interventions to mitigate exposure. The results further emphasise the potential vulnerability of younger children to Chromium exposure, given their physiological susceptibility and frequent interactions with environmental contaminants.

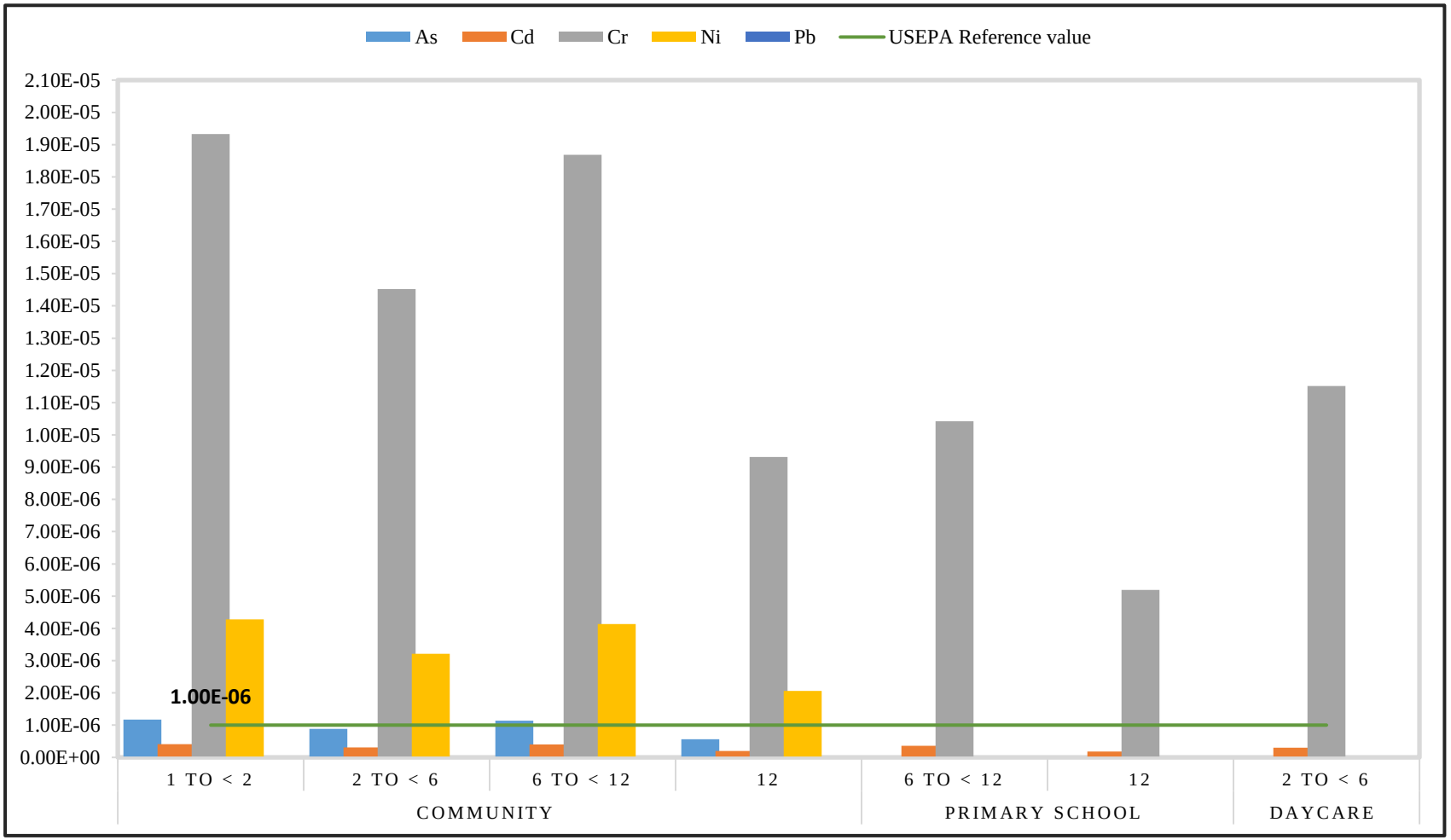


Figure 5: Lifetime Carcinogenic Risk Estimation for Selected Heavy Metal Estimation for Selected Heavy Metals across various Sampling Sites

The study presents critical insights into the health risks associated with Chromium exposure among children aged 1 to 12 years. The estimated lifetime cancer risk for Cr falls within the US EPA's threshold range of 10^{-6} to 10^{-4}, indicating a considerable concern regarding long-term health effects. Specifically, the highest cancer risk was observed in children aged 1 to under 2 years in the community, with a value of 1.93×10^{-5}, highlighting the heightened susceptibility of infants to environmental pollutants. Children aged 6 to under 12 years in the community exhibited a similarly concerning risk level of 1.87×10^{-5}, followed closely by children aged 2 to under 6 years, whose cancer risk was estimated at 1.45×10^{-5}. Furthermore, children aged 2 to under 6 years attending day-care facilities had a risk of 1.15×10^{-5}, while those aged 6 to under 12 years in primary school exhibited a risk of 1.04×10^{-5}. A widespread risk is posed by Chromium exposure across different age groups and environments, necessitating targeted mitigation strategies to reduce exposure in residential and educational settings.

These findings highlight elevated potential for carcinogenic effects of studied heavy metals across these critical age groups, highlighting the need for increased awareness and preventive measures to protect their health. These findings resonate with other research conducted across South Africa, particularly in communities near mining operations [31] [32] [33], where environmental health risks are prevalent. For instance, a comprehensive study in the Mpumalanga Province meticulously assessed the human health repercussions of soil heavy metal contamination in areas affected by coal mining [34] It revealed that the risk of developing cancer from Cr ingestion was substantially higher than from exposure to Arsenic (As) and Cadmium (Cd), clearly exceeding established safety reference values [34].

The current study stands apart from the Mpumalanga research [34] in that, it demonstrates a cancer risk associated with Arsenic exposure that remains below the US EPA reference value of 10^{-6}. In contrast, the Mpumalanga study found that the cancer risk related to Arsenic was significantly higher, exceeding the established reference values [34]. This contrast highlights the differing implications of Arsenic exposure across various geographical contexts.

Worst-case scenario

To plan preventively, the researcher estimated the carcinogenic risk of specific heavy metals in the Kagiso community. This assessment was based on a worst-case scenario derived from the highest concentrations of these metals and the potential longest exposure frequency as shown in table 13.

Table 13 shows the parameters used for evaluation of the worst-case scenario

Table 13: Parameters used for the Estimation of Worst-case Scenario

Age groups in years	Highest concentration recorded for selected heavy metals in mg/g	Exposure frequency in the community as EF(d/yr)
1 to < 2	Arsenic As: 0.0525	350
2 to < 6	Cadmium Cd: 0.0236	350
6 to < 12	Chromium Cr: 0.3951	350
12	Nickel Ni: 0.0672	350
	Lead Pb: 0.01575	350

In a worst-case scenario, as depicted in Figure 6, the carcinogenic risks for children in Kagiso are alarming. For those aged 1 to less than 2 years, significant risk levels are observed for Cr (2.35×10^{-5}) and Ni (1.36×10^{-5}). Among children aged 2 to less than 6 years, there is notable concern regarding As (1.4×10^{-5}), Cr (3.64×10^{-5}), and Ni (2.10×10^{-5}). For the age group of 6 to less than 12 years, the risks associated with As (1.98×10^{-5}), Cr (4.97×10^{-5}), and Ni (2.88×10^{-5}) are particularly concerning. In adolescents aged 12 years and older, significant risks remain for As (9.88×10^{-5}), Cr (2.48×10^{-5}), and Ni (1.43×10^{-5}).

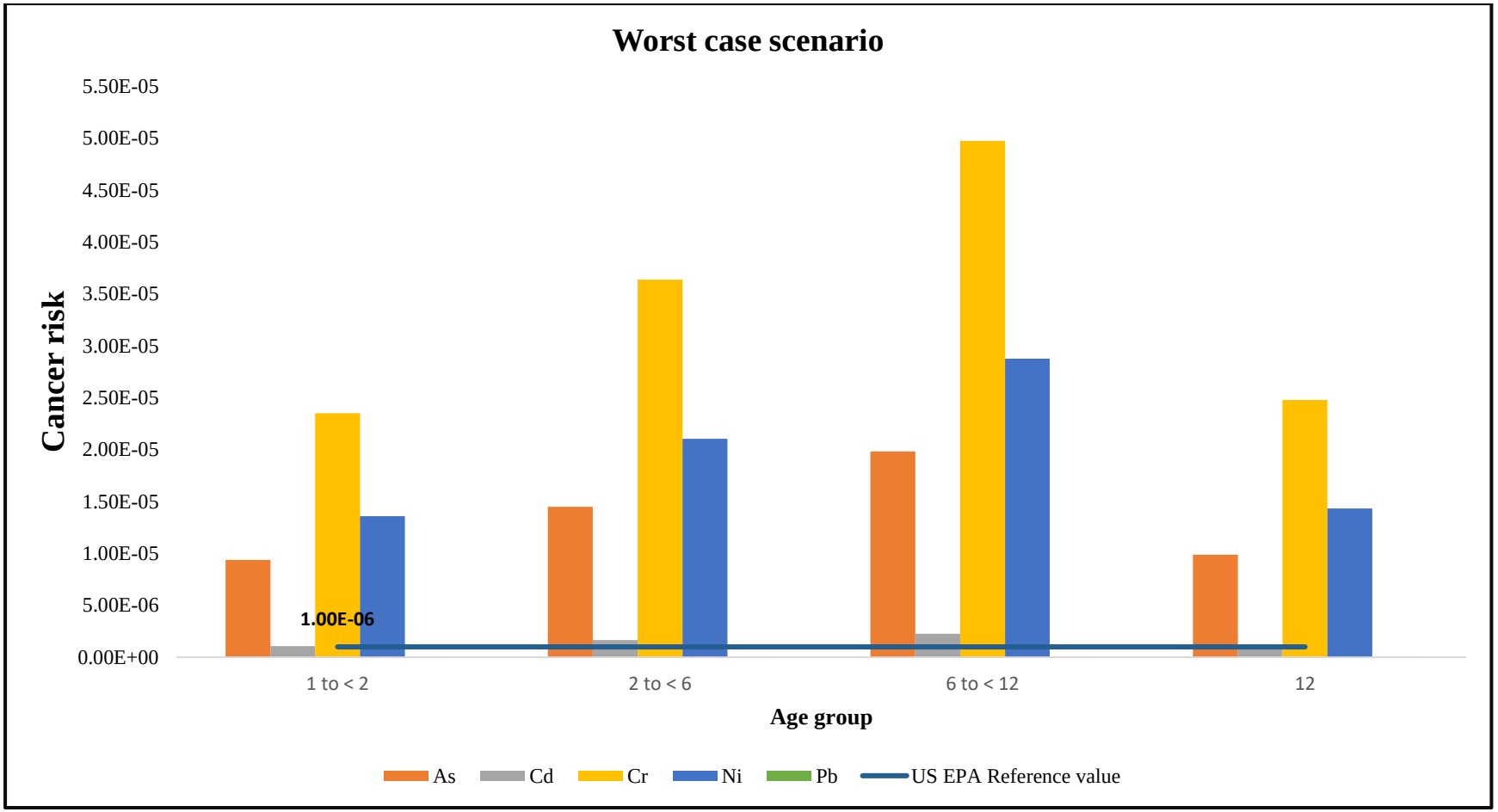


Figure 6: The Worst-case scenario Lifetime Cancer Risk Estimation in Kagiso

Findings, as shown in Figure 6, suggest that all age groups face considerable risks of cancer, predominantly related to As, Cr, and Ni, with the highest concerns identified in the 6 to less than 12-year age group. This research is still consistent with Kamunda's [47] findings in the Witwatersrand basin near gold mines in the Far West Rand, which indicated that As, Cr, and Ni were present at high concentrations and posed carcinogenic risks via ingestion. These suggest that the distribution of heavy metals in the West Rand could be similar due to shared geological and meteorological characteristics [123] [124] [125] [126] .

CHAPTER 5: STRENGTH AND LIMITATION OF THE STUDY

This chapter summarizes the key findings of the study and their implications for environmental and public health. It highlights the research's strengths, which enhance the credibility of the results, while also acknowledging limitations that may affect interpretation.

The chapter also suggests avenues for future research to address existing gaps and concludes with practical recommendations based on the evidence to guide policy and practice.

5.1 Main findings:

Objective 1:

The researcher investigated heavy metal concentrations Pb, Ni, As, Cd, and Cr in soil samples from ecologically sensitive areas in Kagiso. Most locations surpassed acceptable thresholds, particularly around the Tailings Storage Facility (TSF). As levels were significantly elevated near the TSF but decreased at a distance of 100 meters, aligning with South African national standards.

Cd and Cr concentrations exceeded regulatory limits at all sites, especially near the community clinic. Additionally, Nickel levels surpassed World Health Organization (WHO) guidelines at the excavation site, while Lead concentrations near the TSF exceeded only South African standards.

Objective 2:

The researcher examined heavy metal levels in soil samples from various sites near a tailing's storage facility using the Kruskal-Wallis and Wilcoxon rank-sum tests. Results indicated no significant differences in Pb, Cd, Ni, and Cr, as p-values were above 0.05, suggesting a uniform distribution. In contrast, As showed significant variability, with p-values of 0.0540 and 0.0277, indicating contamination related to distance. Overall, Pb, Cd, Ni, and Cr appear uniformly distributed, likely due to widespread environmental dispersion.

Objective 3:

The researcher examined cancer risks associated with heavy metal exposure in the soil of Kagiso, focusing on children aged 1 to 12 years. Significant risks, particularly from Chromium, were identified. The highest risk was observed in children under 2 years, with an

estimate of 1.93×10^{-5}. Other age groups also displayed concerning risk levels for As, Cr, and Ni exposure. These findings underscore the urgent need for protective measures to safeguard children against heavy metal exposure.

5.2 Strength of the Study

This study exhibits several robust strengths in its methodology and analytical approach:

1. The study utilizes non-parametric statistical tests (Kruskal-Wallis and Wilcoxon rank-sum), which are particularly effective for analyzing environmental contamination data that frequently display skewness, zero-inflation, and non-normal distribution. This approach ensures the validity of the findings despite the small sample size and the variability in soil concentrations.
2. The study simultaneously examines multiple toxic metals of significant public health concern As, Cd, Cr, Ni, and Pb allowing for a comparative assessment of distance-related patterns. This multi-metal perspective enhances the interpretation of results, highlighting that As is the only metal exhibiting a significant distance effect, with higher concentrations found at sites closer to the contamination source, while the distribution of the other metals remains relatively uniform.
3. The explicit categorization of sites into Near, Mid, and Far groups provides a clear framework for comparing exposure patterns and enhances the replicability of the research.
4. The findings have direct implications for public health. Given that Arsenic is a well-documented carcinogen, the elevated concentrations observed near the tailing's storage facility suggest a localized exposure risk for surrounding communities.

5.3 Study limitations:

Following an in-depth critical analysis of the current study, several notable limitations emerged:

1. Scope of the Study: This investigation specifically targeted a limited number of carcinogenic heavy metals, with sampling conducted at select facilities in the southern region of Kagiso. This focus on a specific area and subject matter limits the broader applicability of the findings.
2. The analysis of Chromium was based on total concentrations; however, speciation data that distinguishes Cr (III) from Cr (VI) were not available. Since only Cr (VI) is

carcinogenic, the risk assessment assuming 100% Cr (VI) represents a worst-case scenario, which likely overestimates the true risk.

3. Sample Size: The choice to utilize a deliberately small sample size was guided by both logistical considerations and financial constraints. Focusing on this specific area was largely due to the prohibitive costs associated with comprehensive sample analysis and the absence of funding or sponsorship to bolster the researcher's efforts. As a result, this limitation complicates our ability to derive extensive conclusions from the data gathered.
4. Cancer Risk Calculation: A significant aspect of this research was the decision not to assess the overall cancer risk linked to ingestion. The researcher did not incorporate the heavy metals that individuals might consume through contaminated food and water sources in the studied region and the cumulative cancer risk. This omission could lead to an incomplete understanding of the cancer risks related to studied heavy metals faced by the community.
5. Location-Specific Assessments: The cancer risk evaluation was confined to specific locales within Kagiso, notably a day-care Centre, a primary school, and the adjacent community.
6. Exclusion of other Contamination Sources: The researcher did not investigate the impacts of other possible sources of heavy metal contamination in the community, including pollutants emitted from motor vehicles and the extensive use of pesticides. This oversight may result in a lack of understanding regarding the full spectrum of environmental risks.
7. Exclusion of Certain Age Groups: In addition, due to a shortage of data about the weights of South African children under one year and those above 12 years, these critical age groups were regrettably excluded from the researcher's analysis, limiting his insight into their specific vulnerabilities.
8. Measurement Inaccuracies: Lastly, the researcher recognizes the possibility of inaccuracies occurring during the measurement of distances due to the use of GPS, which could adversely affect the reliability and precision of our findings.

In conclusion, while this study offers valuable insights into heavy metal exposure in Kagiso, it also highlights significant gaps that warrant further investigation. A more comprehensive understanding of the risks associated with heavy metals in this community could lead to more effective interventions and policies to protect public health.

5.4 Future Research Avenue

The following can be considered for future research in Kagiso:

1. An extensive soil sample collection across Kagiso for representative sample size for heavy metal soil analysis.
2. A health risk assessment in children for heavy metals exposure through inhalation and dermal exposure routes.
3. A cancer screening in children for identification of heavy metal-related cancer in children.

5.5 Recommendations:

The following comprehensive recommendations are proposed to improve health outcomes and mitigate the risks associated with exposure to carcinogenic heavy metals:

1. Implementing a systematic cancer screening program within the studied population is crucial with focus on skin, nasopharyngeal, lungs and bladder cancer[47] [51]. Early detection of potential cancer cases will enable timely medical interventions, reducing morbidity and mortality associated with heavy metal exposure.
2. Regular health assessments should be conducted for individuals in high-risk areas, with a particular focus on children, who are more vulnerable to the long-term effects of toxic metal exposure. Collaborations with healthcare institutions and government agencies can enhance the effectiveness of such screening initiatives by ensuring adequate resources, trained personnel, and appropriate medical infrastructure.
3. Strengthening legislative measures is equally vital in safeguarding public health. Existing laws concerning buffer zones should be reinforced to ensure that residential areas, schools, and day-care centres maintain a safe distance from potential sources of contamination. Environmental regulations should be revisited to ensure stricter enforcement, holding industries and mining operations accountable for emissions that pose a public health threat. Authorities must conduct routine environmental monitoring and enforce penalties for non-compliance to ensure sustained adherence to regulatory frameworks.
4. Public awareness and education play a fundamental role in preventing exposure-related health risks. A well-structured information campaign should be launched to educate community members about the dangers of heavy metal contamination, emphasizing best practices for minimizing exposure. Schools, healthcare facilities, and local

organizations should be engaged in this process to maximize outreach. Special attention should be given to educating parents and caregivers about reducing exposure risks for young children, particularly in environments where contamination is prevalent.

5. Further research is essential to comprehensively assess the extent of exposure and its long-term health impacts. In-depth follow-up studies should be conducted to quantify exposure levels, evaluate additional risk factors, and track health outcomes over time. These studies should employ advanced methodologies, such as biomonitoring and epidemiological assessments, to provide more precise data on the relationship between environmental pollutants and health risks. Such research will guide policymakers and stakeholders in designing evidence-based interventions, ensuring a proactive approach to addressing environmental health challenges.

CHAPTER 6: CONCLUSION

The study investigation revealed significant levels of heavy metal pollution in the soils of Kagiso, particularly within tailing dumps. The presence of toxic elements such as As, Pb, Cr, Ni, and Cd poses serious health risks, especially for vulnerable populations like children, who face an increased risk of cancer.

The concentrations of these heavy metals varied markedly across different locations. Certain areas, including the soccer field, excavation land, community area, and the community clinic, exhibited levels that exceeded both international and South African safety standards, raising serious concerns about public health. Notably, Cr levels consistently surpassed safety thresholds at most sites, increasing these risks.

The findings of this study are consistent with previous research that documents heavy metal pollution in soils near mining dams, where variations in contamination levels are often observed based on location and the specific types of heavy metals present. However, our study revealed a surprising contradiction at certain sites within the community: the concentrations of As, Cd, and Cr were unexpectedly higher than those recorded at the potential source, the tailing dam. This challenges the conventional understanding that heavy metal levels decrease with increasing distance from the contamination source. Additionally, the researcher found no significant connection between the concentrations of Cd, Cr, Ni, and Pb and the distance to the tailing storage facility, except for As, which showed contamination related to distance. This indicates that more complex environmental dynamics are at play.

In several areas of Kagiso, the lifetime cancer risk for children due to Cr exposure was found to be alarmingly high, exceeding the threshold of 10^{-6} (ranging from 1.04×10^{-5} to 1.93×10^{-5}) but remaining below the 10^{-4} benchmark established by the US Environmental Protection Agency (EPA). Worst-case scenarios indicate significant risks from heavy metals (As, Ni, and Cr) for children. For those under age 2, Cr exposure is 2.35×10^{-5}, and Ni exposure is 1.36×10^{-5}. For children aged 2 to 6, As exposure is 1.4×10^{-5}, Cr is 3.64×10^{-5}, and Ni is 2.10×10^{-5}. Older children and adolescents also face high levels of exposure.

There is an urgent need for extensive research and a collaborative, multidisciplinary approach to effectively address and mitigate the health risks associated with exposure to these hazardous heavy metals. By gaining a deeper understanding of the underlying factors contributing to this contamination, we can better safeguard the health of the community and implement appropriate remediation strategies.

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APPENDIX

Appendix A: Plagiarism declaration

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

FACULTY OF HEALTH SCIENCES

PLAGIARISM DECLARATION TO BE SIGNED BY ALL HIGHER DEGREE STUDENTS

SENATE PLAGIARISM POLICY: APPENDIX ONE

I Badimwena Jacques Tshunza (Student number: 2590078) am a student registered for the degree of MPH Exposure and Health in the academic year 2025.

I hereby declare the following:

- I am aware that plagiarism (the use of someone else's work without their permission and/or without acknowledging the original source) is wrong.
- I confirm that the work submitted for assessment for the above degree is my own unaided work except where I have explicitly indicated otherwise.
- I have followed the required conventions in referencing the thoughts and ideas of others.
- I understand that the University of the Witwatersrand may take disciplinary action against me if there is a belief that this is not my own unaided work or that I have failed to acknowledge the source of the ideas or words in my writing.
- I have included as an appendix a report from "Turnitin" (or other approved plagiarism detection) software indicating the level of plagiarism in my research document.

Signature:  Date: 14 September 2025

Appendix B: Cancer slope factor for heavy metals[201] [202]

Metals	Carcinogenic slope factor in mg/kg day
Chromium (Cr)	0.5
Cadmium (Cd)	0.38
Lead (PB)	0.0085
Nickel (Ni)	1.7
Arsenic (As)	1.5

Appendix C: Soil and dust ingestion rate[191].

Table 5-1. Recommended Values for Daily Soil, Dust, and Soil + Dust Ingestion (mg/day)[a]

	Soil + Dust		Soil[b]				Dust[c]	
Age Group	General Population Central Tendency[d]	General Population Upper Percentile[e]	General Population Central Tendency[f]	General Population Upper Percentile[f]	Soil Pica[g]	Geophagy[h]	General Population Central Tendency[f]	General Population Upper Percentile[f]
<6 months	40	100	20	50	—	—	20	60
6 months to <1 year	70 (60–80)	200	30	90	—	—	40	100
1 to <2 years	90	200	40	90	1,000	50,000	50	100
2 to <6 years	60	200	30	90	1,000	50,000	30	100
1 to <6 years	80 (60–100)	200	40	90	1,000	50,000	40	100
6 to <12 years	60 (60–60)[i]	200	30	90	1,000	50,000	30	100
12 years through adult	30 (4–50)[j]	100[j]	10	50	—	50,000	20	60

[a] Ranges are provided in parentheses, when applicable, and represent the range of means from the various studies. Ranges are not provided for age groups for which the recommendations are based on a single study.

[b] Includes soil and outdoor settled dust.

[c] Includes indoor settled dust only.

[d] Based on the average of the central tendency values from the various studies for each of the three methodologies (tracer, biokinetic modeling, activity pattern), averaged over the three methods. Recommendation for <6 months of age based on Wilson et al. (2013) (note that data for 0 to <7 months in Wilson et al. [2013] were used to represent the 0 to <6 months age group). Recommendations for children 6 months to <1 year based on the average of values from Hogan et al. (1998) and von Lindern et al. (2016). Recommendations for 1- to 2 year-olds and 2- to <6-year-olds based on von Lindern et al. (2016). Recommendations for children ages 1 to <6 years based on the average of values from Calabrese et al. (1989) as reanalyzed in Stanek and Calabrese 1995a (mean of the median values for the best 4 tracers for each child); Calabrese et al. (1997a) (average of the best tracer for each child); Calabrese et al. (1997b) (average of aluminum and silicon); Davis et al. (1990) as reanalyzed by Stanek and Calabrese, 1995a (mean of the median values for 3 tracers for each child); Hogan et al. (1998); Özkaynak et al. (2011); von Lindern et al. (2016); and Wilson et al. (2013). The recommendations for ages 12 years to adults are based on the average of data for teens (ages 12 to <20 years), adults, and seniors from Wilson et al. (2013) and on adults from Davis and Mirick (2006). All recommended values were rounded to one significant figure. See Table 5-34 for additional details.

[e] Based on the average of the 95th percentile values from the various studies for each of the three methodologies (tracer, biokinetic modeling, activity pattern), averaged over the three methods. Based on the 95th percentile values for the same studies as used for the central tendency estimates except for age 12 years through adults. Upper percentile recommendation for 12 years of age through adults based on the assumption that the ratio of the 95th percentile to the mean value for adults is the same as the average of the ratios of 95th percentiles to means for all other age groups (i.e., average ratio of the 95th percentile to mean recommendations = 3.2). See Table 5-34 for additional details.

[f] Estimates of soil and dust were derived from the soil + dust values assuming 45% soil and 55% dust, rounded to one significant figure.

[g] Professional judgement based on: ATSDR (2001); Barnes (1990); Calabrese et al. (1997b, 1991, 1989); Stanek et al. (1998).

[h] Vermeer and Frate (1979).

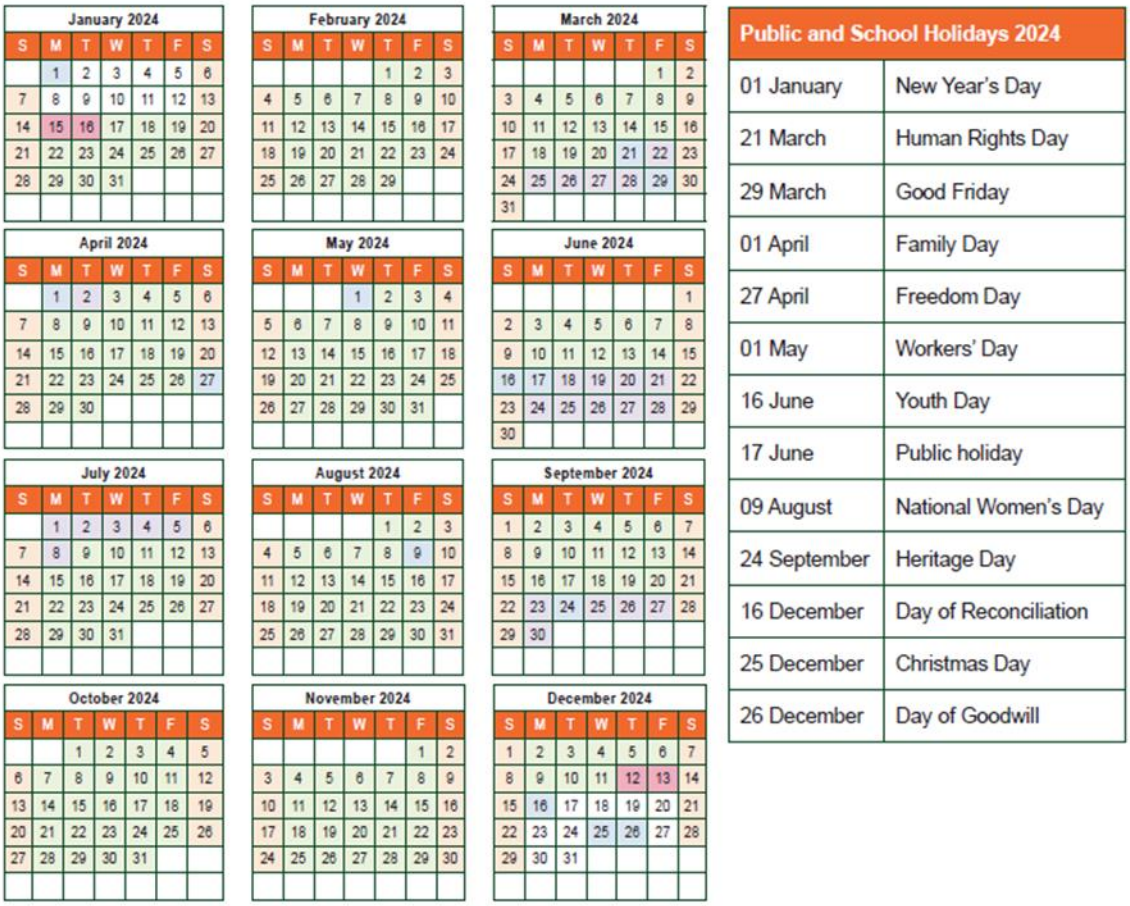
[i] Range based on two studies with estimates of 55 and 56 mg/day; both of these estimates round to 60 mg/day.

[j] Soil + dust ingestion rates may be higher for adults following a traditional rural or wilderness lifestyle. Based on Doyle et al. (2012) and Irvine et al. (2014) the central tendency adult soil + dust ingestion rates is 50 mg/day (20 mg/day soil and 30 mg/day dust) and the upper percentile rate is 200 mg/day (90 mg/day soil and 100 mg/day dust).

— = No data.

Appendix D: 2024 South African school calendar for public schools[195]

2024 SCHOOL CALENDAR



Public and School Holidays 2024	
01 January	New Year's Day
21 March	Human Rights Day
29 March	Good Friday
01 April	Family Day
27 April	Freedom Day
01 May	Workers' Day
16 June	Youth Day
17 June	Public holiday
09 August	National Women's Day
24 September	Heritage Day
16 December	Day of Reconciliation
25 December	Christmas Day
26 December	Day of Goodwill

Weekends	School days	Special school holidays
Days for administration	Public holidays	School holidays

SUMMARY OF 2024 SCHOOL CALENDAR

Duration	No. of weeks	No. of days	No. of public holidays	Actual no. of school days
(15) 17 January – 20 March	10	46 (48)	0	46 (48)
03 April – 14 June	11	53	1+0	52
09 July – 20 September	11	54	1+0	53
01 October – (11) 13 December	11	52 (54)	0	52 (54)
Total	**43**	**205 (209)**	**2+0**	**203 (207)**

Appendix E: The South African children's mean weight[197]

Age (years)	Mean weight (kg)	Mean weight Male (kg)	Mean weight Female (kg)
1	10.8	10.7	10.8
2	12.7	12.8	12.5
3	14.6	14.7	14.3
4	16.4	16.5	16.3
5	18.8	19.1	18.4
6	20.6	20.8	20.2
7	23.7	23.6	23.8
8	25.2	25.1	25.4
9	29.0	28.8	29.5
10	32.5	31.8	33.8
11	35.5	34.8	36.6
12	39.3	38.4	41.9

Appendix F: Waiver over ethics clearance of research

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

Office of the Deputy Vice-Chancellor (Research & Innovation)

TO: Dr BJ Tshunza
School: Public Health
Department: Occupational Health
Division:
Medical School
University
E-mail: jacquestshunzab@gmail.com

CC: Supervisor: Dr T Makonese Tafadzwa.Makonese@wits.ac.za
and <HREC-Medical.ResearchOffice@wits.ac.za>

FROM: Mr Iain Burns
Human Research Ethics Committee (Medical)
Tel: 011 717 1252

E-mail: Iain.Burns@wits.ac.za

DATE: 29/11/2023

REF: *R14/49*

PROTOCOL NO: W-PR-231129-02 (This is your ethics application study reference number. Please quote this reference number in all correspondence relating to this study)

PROJECT TITLE: *Health risk assessment of exposure to heavy metals in soils near mine dumps*

Please find attached the Ethics Waiver Certificate for the above project. I hope it goes well and that an article in a recognized publication comes out of it. This will reflect well on your professional standing and contribute to the Government funding of the University.

MSWorks2000/Iain0007/ClearScanWaiver.wps

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

Office of the Deputy Vice-Chancellor (Research & Innovation)

29/11/2023

Ref: W-PR-231129-02

TO WHOM IT MAY CONCERN

Waiver: This certifies that the following research does not require clearance from the Human Research Ethics Committee (Medical)

Investigator: Dr BJ Tshunza
Student No. (if appropriate): 2590078
Staff No. (if appropriate):

Supervisor: Dr T Makonese

School: Public Health
Department: Occupational Health
Division:
Medical School
University

Project title: *Health risk assessment of exposure to heavy metals in soils near mine dumps*

Reason: In vitro laboratory study
No human participants will be involved in the study

Professor P Ruff
Chairperson: Human Research Ethics Committee (Medical)

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