

**EVALUATION OF POTENTIAL NON-CARCINOGENIC HEALTH RISK  
FROM INHALATION OF HEAVY METALS IN CONTAMINATED  
SOIL ,IN IMEKE ETSAKO-WEST IN EDO STATE, NIGERIA.**



**BY**

**Osarugue Sharon UHUNMWUAGHO (Miss)**

**LSC2007358**

**DEPARTMENT OF SCIENCE LABORATORY TECHNOLOGY**

**(GEOLOGY AND MINING TECHNIQUES)**

**FACULTY OF LIFE SCIENCES**

**UNIVERSITY OF BENIN**

**BENIN CITY**

**NOVEMBER, 2025.**

**CERTIFICATION**

I hereby certify that this thesis **EVALUATION OF POTENTIAL NON-CARCINOGENIC HEALTH RISK FROM INHALATION OF HEAVY METALS IN CONTAMINATED SOIL, IN IMEKE ESTAKO-WEST IN EDO STATE, NIGERIA** was carried out by **Osarugue Sharon UHUNMWUAGHO (Miss)** with matriculation number **LSC2007358** of The Department of Science Laboratory Technology (Geology and Mining Techniques), Faculty of Life Sciences, University of Benin, Benin City under the supervision of Dr. K. OJEAGA

\_\_\_\_\_  
**Dr. K. OJEAGA**  
**(Project Supervisor)**

\_\_\_\_\_  
**Date**

\_\_\_\_\_  
**Dr. P. O ALONGE**  
**(Project Coordinator)**

\_\_\_\_\_  
**Date**

\_\_\_\_\_  
**Prof. J. O. OSARUMWENSE**  
**(Head of Department)**

\_\_\_\_\_  
**Date**

\_\_\_\_\_  
**External Examiner**

\_\_\_\_\_  
**Date**

## **DEDICATION**

I dedicate this work to God Almighty, whose unwavering guidance, direction and strength have fueled my journey of discovery. And also my grandparents Pa G.O ogbonwan and late Mrs patience taiwo ogbonwan.

## ACKNOWLEDGMENT

With profound gratitude, I acknowledge God Almighty for his unwavering grace, strength, and guidance throughout this academic journey. His favor and wisdom have been my anchor in overcoming challenges and successfully completing this project.

I extend my heartfelt gratitude to my supervisor, Dr. K. Ojeaga, for his guidance, unwavering support, and insightful feedback throughout the course of this research project. I am deeply thankful to my Head of Department, Prof. J. O. Osarumwense, and the entire staff of science laboratory technology for providing a conducive academic environment and fostering a culture of excellence within the department. I also appreciate my friends: Precious, Efemena, Akachi, Knowledge, Kevwe, Mercy, Hannah, Joanita, Glory Boi, Ehi and my amiable option rep Omoregbe Precious, thank you for the constant encouragement, motivation, and your companionship has been priceless. The shared moments of laughter, intellectual discussions and unwavering support made this academic pursuit worthwhile and to my colleagues geology and mining class of '25 I love and appreciate you all.

I owe a debt of gratitude to my parents, Mrs. Joy Oghogho Ogbonwan and Mr. Charles Uhumwuagho for their unconditional love, financial sacrifices, prayers and moral support which has been my driving force. To my wonderful siblings Uhumwuagho Osakpolor, Uhumwuagho Osamwonyi and my amiable big sister Mrs. Gift Okosun. My uncle Dr. Igie Ogbonwan and his lovely family and my family at large thank you for always believing in me and standing by me throughout this journey.

Lastly I would like to thank myself for not giving up and pushing through, I am immensely grateful to everyone who, in one way or another, contributed to the success of this academic endeavor. May God bless and reward you all abundantly.

## ABSTRACT

Heavy metal contamination in soils has become a critical environmental and public health concern, particularly in regions affected by anthropogenic activities such as mining, industrialization, and poor waste management. This study evaluates the potential non-carcinogenic health risks associated with the inhalation of heavy metals in contaminated soils within Imeke, Etsako-West Local Government Area, Edo State, Nigeria. Soil samples were systematically collected from varying depths across the study area and analyzed for selected heavy metals, including lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), arsenic (As), copper (Cu), zinc (Zn), and iron (Fe), using Atomic Absorption Spectrophotometry (AAS). Standard geochemical indices such as the Enrichment Factor (EF), Geo-accumulation Index (Igeo), and Pollution Load Index (PLI) were employed to assess the extent of metal contamination. Health risk assessment was conducted following the United States Environmental Protection Agency (USEPA, 1989; 2004) guidelines, focusing on non-carcinogenic exposure pathways through inhalation. Parameters such as the Average Daily Dose (ADD), Hazard Quotient (HQ), and Hazard Index (HI) were computed for both adults and children populations to quantify potential health impacts. The results revealed varying degrees of heavy metal enrichment, with some metals exceeding permissible limits, indicating moderate to considerable contamination. The calculated hazard indices for certain metals exceeded the acceptable threshold ( $HI > 1$ ), suggesting potential adverse health effects, particularly among vulnerable populations. The study underscores the significance of continuous monitoring, effective land-use planning, and implementation of remediation measures to mitigate the health implications of soil-borne heavy metals in the study area.

## TABLE OF CONTENTS

CERTIFICATION.....	ii
DEDICATION.....	iii
ACKNOWLEDGMENT.....	iv
ABSTRACT.....	v
CHAPTER ONE.....	1
INTRODUCTION.....	1
Background of Study.....	1
1.1. Aim and Objectives.....	6
1.2. Statement of the Problem.....	7
1.3. Justification of the Study.....	7
CHAPTER TWO.....	9
LITERATURE REVIEW.....	9
2.0. Overview.....	9
2.1. Trends in the field of health risk assessment of HMs in soil and sediment.....	15
2.2. Health risk assessment.....	16
2.3. Average daily dose.....	17
2.4. Carcinogenic risk.....	18
2.5. Ingestion rate (IngR).....	19
2.6. Inhalation rate (InhR).....	19

2.7. Exposure frequency (EF).....	20
2.8. Exposure duration (ED).....	20
2.9. Particulate emission factor (PEF).....	21
2.10. Skin surface area (SA).....	21
2.11. Adherence factor (AF).....	22
2.12. Dermal absorption factor (ABS).....	22
2.13. Body weight (BW).....	23
2.14. Reference dose (RfD).....	23
2.15. Cancer slope factor (CSF).....	24
2.16. Review of related literature.....	25
CHAPTER THREE.....	32
MATERIALS AND METHOD.....	32
3.0. REGIONAL GEOLOGY.....	32
3.0.1. Migmatite-gneiss formations.....	33
3.0.2. Granitoid intrusions.....	34
3.0.3. Mineralogical composition.....	34
3.0.4. Hydrogeological and structural controls on groundwater.....	34
3.1. LOCAL GEOLOGY.....	35
3.2. MATERIALS.....	35
3.3. METHODS.....	35

3.3.1 Sample Collection.....	35
3.3.2. Laboratory analysis.....	36
3.3.3. Human Health Risk Assessment: Ingestion Pathway.....	36
3.3.4. Chronic Daily Intake (CDI).....	36
3.3.5. Ecological risks of heavy metals in groundwater.....	37
3.3.6. Health risks of Heavy metals in groundwater.....	37
3.3.7. Determination of non-carcinogenic risk.....	38
3.3.8. Hazard index for children and adults.....	39
3.3.9. Carcinogenic risk assessment.....	39
3.3.10. Statistical Analysis.....	40
CHAPTER FOUR.....	41
RESULTS AND DISCUSSION.....	41
Table 4.1: Concentrations of Heavy Metals in Soil Samples and comparison with WHO and EPA standards.....	41
Table 4.2: Chronic Daily Intake (CDI) via Inhalation for Adults and Children.....	42
Table 4.3: Hazard Quotient (HQ) via Inhalation.....	42
Table 4.4: Hazard Index (HI).....	42
4.1.2. Non-carcinogenic Risk Assessment.....	43
CHAPTER FIVE.....	45
CONCLUSION AND RECOMMENDATION.....	45
5.0. Conclusion.....	45

5.1. Recommendations.....45

REFERENCES..... 46

# CHAPTER ONE

## INTRODUCTION

### Background of Study

Heavy metals (HMs) constitute a broad group of metallic and metalloid elements noted for their high atomic density, ranging from approximately 3.5 to 7 g/cm<sup>3</sup> depending on the classification source and their toxicity to biotic systems, even at minimal exposure levels (Gradinaru *et al.*, 2019). The environmental distribution of these elements is influenced by their physicochemical properties and prevailing ecological conditions, factors which have facilitated their exploitation by human civilizations for millennia (Kesler *et al.*, 2015). However, their persistent accumulation in terrestrial, atmospheric, and aquatic environments now represents a critical ecological hazard. HMs exhibit long-term environmental persistence and a high potential for bioaccumulation, particularly within human biological systems, where deleterious effects are observable at low concentration thresholds (Verma *et al.*, 2023). Elements such as cadmium (Cd), lead (Pb), arsenic (As), hexavalent chromium (Cr VI), nickel (Ni), and mercury (Hg) lack any known biological function and are associated with severe health outcomes even at trace levels (Coleman *et al.*, 2017). In contrast, essential metals like copper (Cu) and iron (Fe), while indispensable for metabolic processes, become toxic when their concentrations exceed physiological thresholds. Likewise, other micronutrients such as cobalt (Co), selenium (Se), and zinc (Zn) may exert harmful effects in cases of excessive exposure (Font *et al.*, 2019). Both acute and chronic exposure to these elements has been linked to adverse health outcomes (Hwang *et al.*, 2014). According to the priority ranking of hazardous substances by the Agency for Toxic Substances and Disease Registry, As, Pb, Hg, and Cd are among the most toxic, occupying the top four of the list (IARC, 2019). Epidemiological and experimental studies in vitro and in vivo

suggest a strong correlation between prolonged exposure to As, Ni, and Cr and increased carcinogenic risk (Ali *et al.*, 2019; Elsayed *et al.*, 2016). Historical documentation of cancer cases among workers exposed to these elements' dates back to the 19th century (Rehman *et al.*, 2018).

The proliferation of industrialization across both developed and developing nations has substantially intensified the demand for non-ferrous metals, some of which are carcinogenic, thereby escalating environmental and occupational exposure (Khlifi and Hamza-Chaffai, 2010). Substances such as asbestos, Pb, Hg, and Cd, although naturally occurring, have become widespread contaminants primarily due to anthropogenic activities (Havugimana *et al.*, 2017). Industrial processes remain a major conduit for HM exposure, especially in countries with rapidly expanding manufacturing sectors. In the United States, large swaths of land have been designated as "brownfields" or "Superfund" sites due to historical contamination linked to unsustainable industrial and waste disposal practices (Rehman *et al.*, 2018). Furthermore, indoor pollutant concentrations in industrial settings can exceed outdoor levels, exacerbating the exposure risk (Mousavian *et al.*, 2017).

Industrial emissions not only impact environmental integrity but also significantly affect the health and well-being of the workforce. Workers' exposure to toxic metals is closely linked to occupational conditions, socioeconomic factors, and labor policies, all of which influence vulnerability to HM-related health outcomes (Isinkaralar *et al.*, 2024; Tamers *et al.*, 2020; Khoshakhlagh *et al.*, 2024). In particular, the metal processing sector, including welding and alloy smelting, frequently exposes workers to elevated levels of Cr, Cd, Mg, Ni, and Pb. These exposures have been correlated with a heightened incidence of cancers affecting the upper

respiratory tract, such as nasopharyngeal and laryngeal carcinomas, due to inhalation of metal particulates and prolonged exposure to industrial heat sources (Feary and Cullinan, 2019; Nikkilä *et al.*, 2023). A study by Liu *et al.* (2009) highlighted significant occupational HM exposure among foundry workers, with the concentrations of Cd, Cr, and Ni surpassing the recommended non-carcinogenic risk threshold of  $1 \times 10^{-6}$ , registering values of  $2.34 \times 10^{-4}$ ,  $7.92 \times 10^{-3}$ , and  $5.76 \times 10^{-5}$ , respectively. Comparative assessments of airborne HM profiles across various industrial environments reveal that foundries generally emit higher concentrations than other manufacturing or administrative facilities (Marcias *et al.*, 2019; Scott *et al.*, 2021).

Given these findings, researchers have emphasized the need for further investigation into additional health consequences such as pulmonary dysfunction, bronchial pathologies (Cullinan *et al.*, 2017; Gorka-Kostrubiec, 2015), and potential neurobehavioral impairments among industrial laborers (Rohlman *et al.*, 2012). Empirical evidence suggests that exposure to HMs in industries such as battery production, cement manufacturing, and metal recycling may contribute to DNA damage and genotoxic stress among workers (Chen *et al.*, 2006; Liu *et al.*, 2009).

The accumulation of potentially harmful metals like cadmium (Cd), nickel (Ni), chromium (Cr), copper (Cu), and manganese (Mn) in water, food, and soil has emerged as a significant global public health challenge. While these metals naturally occur in the environment, human-driven activities such as intensive farming, poor waste disposal practices, and industrial processes have led to heightened concentrations in ecological systems (Khatoon *et al.*, 2025). Certain trace metals including copper (Cu), zinc (Zn), cobalt (Co), iron (Fe), and manganese (Mn) are crucial for human physiological functions (Khatoon *et al.*, 2025). These elements play essential roles in signaling pathways and numerous metabolic activities. However, when present in excessive

quantities, even these beneficial metals may exhibit toxic and carcinogenic properties (Ahmed *et al.*, 2021). Conversely, metals like cadmium (Cd), nickel (Ni), lead (Pb), mercury (Hg), and chromium (Cr) are harmful even at trace concentrations, contributing to serious health conditions such as cancer, cardiovascular disorders, hypertension, and cognitive impairments (Aendo *et al.*, 2022; Ahmed *et al.*, 2020). The primary concern with toxic metals stems from their inherent toxicity, environmental persistence, and tendency to bioaccumulate in organisms. Their ability to persist and build up within living systems renders them a serious threat to human health (Khatoon *et al.*, 2025).

According to the International Agency for Research on Cancer (IARC, 1999), cadmium (Cd), chromium (Cr), and nickel (Ni) are classified as Group 1 human carcinogens. Research indicates that cadmium exposure is linked to cancers of the lungs, breast, prostate, kidneys, and pancreas. Cadmium can trigger cancer by interfering with epigenetic regulation, disrupting cellular signaling, generating oxidative stress, and inducing DNA damage (Waalkes and Misra, 2023). Additionally, cadmium impairs DNA repair mechanisms, further promoting tumor progression (Cirovic and Satarug, 2024). Chromium has been implicated in nasal, stomach, and pulmonary cancers, primarily through its ability to alter tumor suppressor genes, cause chromosomal instability, and produce reactive oxygen species (ROS) that damage DNA (Khatoon *et al.*, 2025). Nickel exposure has been shown to result in malignancies of the nasal passages, lungs, and throat via mechanisms involving ROS generation, DNA methylation changes, repression of tumor suppressor genes, and epigenetic alterations, ultimately hindering cellular DNA repair processes (Zhao *et al.*, 2022). Although manganese (Mn) is not directly associated with cancer development, chronic overexposure can lead to oxidative stress and neurotoxicity, potentially

facilitating cancer progression in the presence of other toxic metals like Cd, Ni, and Cr (Gandhi *et al.*, 2022).

Over the past seven decades, cancer has caused approximately 9.6 million deaths globally, with 18.1 million new diagnoses recorded. Alarmingly, cancer ranks as the leading cause of mortality in 91 out of 172 countries. Projections for 2040 suggest an increase to 29.5 million new cancer cases and 16.3 million cancer-related deaths (Khatoon *et al.*, 2025). Contributing factors to these escalating rates include urban sprawl, population aging, sedentary behavior, unhealthy diets, and deteriorating environmental conditions (Khatoon *et al.*, 2025). Studies have revealed a strong correlation between heavy metal exposure and the incidence of thyroid cancer. Elevated concentrations of toxic metals were found in urine samples from residents near Mount Etna in Sicily (Giani *et al.*, 2021). A global analysis of heavy metal exposure in breast cancer patients from five continents found that biological samples consistently exhibited increased levels of toxic metals (Liu *et al.*, 2022). Recent epidemiological studies have highlighted the alarming connection between exposure to these metals and the increased prevalence of various cancers among exposed populations (Khatoon *et al.*, 2025).

The United States Environmental Protection Agency (USEPA) has developed health indices to evaluate and communicate the potential health impacts of heavy metal exposure on individuals and communities (Baltas *et al.*, 2020). These indices combine data on exposure levels, toxicity thresholds, and individual susceptibility to calculate parameters like the total hazard quotient (THQ), hazard index (HI), and lifetime cancer risk (CR) (Mohammadi *et al.*, 2020). The HI, in particular, allows for the identification of high-risk exposures, enabling health officials and policymakers to prioritize and implement suitable protective measures (Sajjadi *et al.*, 2022).

These analytical tools enhance the precision of health risk evaluations and support informed decisions in environmental health management by assessing various metals and their pathways of exposure (Ogarekpe *et al.*, 2023). Their application is especially vital in developing nations, where lax regulations and unchecked industrial activities often lead to severe metal contamination, putting public health at considerable risk (Chorol and Gupta, 2023). Individuals residing in areas with high levels of heavy metal contamination face heightened exposure risks. The likelihood of coming into contact with contaminated water, soil, or food rises substantially in regions with dense industrial operations or weak environmental oversight (Khatoon *et al.*, 2025). As Yakameran *et al.* (2021) report, these hazardous substances can infiltrate the body via ingestion, inhalation, or dermal absorption, accumulating in vital tissues and organs once internalized (Koch *et al.*, 2022).

### **1.1. Aim and Objectives**

The aim of this study is to evaluate the potential non-carcinogenic risks exposure of metals in the area of study.

The objectives are;

- To determine the concentrations of selected heavy metals in varying depths from soil samples in the study area.
- To evaluate the extent of heavy metal contamination and pollution in the study area, using indices such as the Enrichment Factor (EF), Geo-accumulation Index (I<sub>geo</sub>), and Pollution Load Index (PLI).
- To analyze the potential non-carcinogenic health risks linked to individual heavy metals for both children and adult populations.

## **1.2. Statement of the Problem**

Soil contamination by heavy metals has become a significant environmental and public health issue, particularly in regions influenced by anthropogenic activities such as mining, industrial operations, and improper waste disposal. Among the various exposure pathways, inhalation of contaminated soil particulates represents a critical and often under appreciated route, especially in areas with dry climates, high human activity, or disturbed soils that facilitate airborne dust generation. Non-carcinogenic effects of heavy metals such as neurotoxicity, nephrotoxicity, respiratory distress, and developmental disorders, are well-documented in toxicological literature. Metals such as lead (Pb), cadmium (Cd), chromium (Cr), and manganese (Mn) can pose considerable health risks when inhaled in particulate-bound forms. Vulnerable populations, particularly children and individuals with pre-existing respiratory conditions, are disproportionately affected. Hence, an evidence-based evaluation of the potential health risks arising from the inhalation of heavy metals in contaminated soils is essential to guide environmental health interventions, urban planning, and land-use policies.

## **1.3. Justification of the Study**

The evaluation of non-carcinogenic health risks from inhalation of heavy metals in contaminated soils is crucial for public health protection and sustainable environmental management. Inhalation exposure is particularly relevant in urban, peri-urban, and industrial zones where dust resuspension from contaminated soil surfaces contributes significantly to human metal intake. This study provides a scientific basis for quantifying health risks through an exposure-specific lens, by focusing on the inhalation route, which is often less addressed. The study also enhances the comprehensive nature of environmental risk assessments. The findings will also contribute to

informed decision-making in environmental health policy, especially in regions experiencing rapid land-use changes and increased anthropogenic soil disturbances.

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.0. Overview

Soil plays a pivotal role in environmental studies, serving as a medium where complex interactions among minerals, air, water, and biota occur. Compared to air and water, soil exhibits a slower response to external influences due to its capacity to adsorb and integrate substances into its matrix. This retention capability, while beneficial for nutrient cycling, also facilitates the accumulation of environmental pollutants (Luo *et al.*, 2007a; Qishlaqi *et al.*, 2009). The contamination of surface soils with hazardous trace metals poses considerable health hazards, particularly through ingestion (Luo *et al.*, 2011; Okorie *et al.*, 2011), inhalation of dust and airborne particulates (Laidlaw and Filippelli, 2008), and dermal exposure, especially in areas designated for residential and recreational use (Luo *et al.*, 2012). The health implications of soil-bound trace metals largely depend on their bioavailability, meaning only a portion of the total metal content may be accessible for absorption in humans (Luo *et al.*, 2011; Luo *et al.*, 2012). Traditionally, assessments of soil pollution have relied on total or pseudo-total concentrations of metals, benchmarked against soil guideline values (Morton-Bermea *et al.*, 2009). However, such metrics can potentially overestimate the real health risks posed to humans (Elless *et al.*, 2007; Peijnenburg *et al.*, 2007).

In recent years, the focus on the bioavailability of trace metals in soil has gained momentum among researchers (An and Kampbell, 2003). The term "bioavailable fraction" refers to the portion of a chemical within an environmental matrix that is either directly available or can become available for uptake by organisms or plants within a specific timeframe, either from the immediate environment or through ingestion of contaminated food sources (Peijnenburg and

Jager, 2003). A range of methodologies has been proposed to assess the mobility and reactivity of metals, encompassing both their physicochemical properties and biologically accessible form. Among the most commonly employed techniques is chemical extraction using various reagents of differing strengths, which provides operational definitions for specific metal fractions (Meers *et al.*, 2007). Typical extractants include weak solvents like water or salt solutions, reducing agents, dilute acids, chelating compounds, and mixtures of salts and acids (Peijnenburg *et al.*, 2007). The underlying premise of these techniques is that the extracted metal fractions are sufficiently mobile and may pose risks to soil organisms (Luo *et al.*, 2012). Despite this, numerous studies have evaluated human health risks by focusing solely on the oral ingestion pathway of trace metals in soil (Guney *et al.*, 2010; Hu *et al.*, 2011).

Heavy metals such as Ba, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, V, and Zn, along with metalloids including As, Sb, Ge, and Te, collectively referred to as HMs, have been integral to human development over centuries (Raymond, 1986). These elements are employed across diverse industrial and commercial sectors, including construction, electronics, and transportation (Vidal *et al.*, 2017). With ongoing population growth and economic expansion, the global demand for HMs has steadily increased. Among their most notable applications is in steel production, a fundamental material used extensively in the building of infrastructure such as bridges, buildings, and transport networks. Elements like Fe, Ni, and Cr are crucial constituents in the composition of steel, rendering them economically indispensable. Additionally, HMs are vital components in the fabrication of modern electronic devices such as smartphones, laptops, and related technologies. The extraction and processing of these metals also contribute to job creation for millions globally (Miletic *et al.*, 2023).

Naturally, heavy metals exist in geological materials in the form of compounds, predominantly sulfides and oxides. The most prevalent metal ores include sulfides of Fe, As, Pb, Pb–Zn, Co, Au, Ag, and Ni, as well as oxides of Al, Mn, Se, Au, and Sb. Often, multiple sulfide or oxide forms coexist in a single ore body. For example, pyrite ( $\text{FeS}_2$ ) frequently occurs in association with sulfides of Cu, Pb, Cd, As, and Hg. Elevated concentrations of HMs in soil may result from geochemical processes such as acid Mine Drainage. This phenomenon arises when sulfur-bearing ores interact with oxygen and water to form sulfuric acid, consequently generating acidified waters rich in heavy metals (Mohammed *et al.*, 2011). Nonetheless, human activities like mining and smelting remain major anthropogenic sources of HM contamination. These activities release significant quantities of toxic metals into the environment (Chu *et al.*, 2022; Gui *et al.*, 2023). Contaminants such as Cd, As, Cu, Cr, Hg, Pb, and Zn are introduced into ecosystems through mining operations (Dragovic *et al.*, 2013), where they can be transported over long distances by wind or water or persist as tailings (Kou *et al.*, 2022). Soil in regions distant from the original contamination site can still exhibit elevated HM levels (Weissmannová *et al.*, 2019). This issue is particularly severe in developing nations, where environmental regulations are often inadequately enforced. Consequently, improper waste handling facilitates HM release into ecosystems, creating substantial environmental risks (Jiménez-Oyola *et al.*, 2021). To evaluate the potential human health impacts in such scenarios, health risk assessments are frequently conducted in mining and smelting zones (Chen *et al.*, 2022).

While soil serves as a reservoir of essential nutrients, it also acts as a sink for heavy metals, whose presence in excess raises serious environmental and health concerns. In soils, HMs occur in various chemical forms that differ in terms of their mobility, bioavailability, and reactivity (Oves *et al.*, 2012). These forms may include exchangeable ions, soluble inorganic or

organic complexes, metals bound to carbonates, oxides of iron and manganese, solid-state organic matter, or residual fractions. Importantly, the fraction of HMs that is bioavailable does not necessarily correlate with total concentrations in soil. Due to their high toxicity, HMs present significant threats to ecosystems and human populations alike. Elements such as As, Cr, Hg, Pb, and Cd are of particular concern due to their potential to cause severe health issues in humans, plants, and animals. Once deposited in soil, these metals can disrupt physiological functions in plants and eventually enter the food chain, affecting human health. Soil fertility and biological functions are also adversely affected. The concentration of HMs in soil is influenced by varying soil properties, which explains the observed differences in HM content across soil types (Miletic *et al.*, 2023).

Similarly, sediments function as long-term repositories of HMs, with considerable implications for both ecological and human health through food chain contamination. Once HMs enter aquatic systems, they often settle into sediments, which then serve as sinks for these contaminants. This process alters the chemical properties of water and disrupts aquatic system functioning. The quality of water bodies is consequently diminished. Contaminated sediments impact aquatic life by enabling the accumulation of HMs in organism tissues, eventually reaching humans through trophic transfer (Miletic *et al.*, 2023). Monitoring the levels of HMs in aquatic environments is therefore critical, as these measurements provide valuable insights into ecosystem health (El-Alfy *et al.*, 2021; Ustaoglu *et al.*, 2020).

Beyond environmental consequences, heavy metals pose direct threats to human well-being (Huang *et al.*, 2018). Prolonged exposure to HMs leads to bioaccumulation in the human body, contributing to the onset of both acute and chronic illnesses (Zhang *et al.*, 2020). Accumulated HMs can impair multiple organ systems, including the immune, nervous,

cardiovascular, endocrine, and skeletal systems (Doležalová *et al.*, 2019). Human exposure can occur through various routes with primary pathways including direct contact with contaminated soils via ingestion, inhalation, or dermal absorption. Indirect exposure may also arise through the consumption of crops cultivated on polluted soils. Thus, assessing HM contamination in agricultural lands is essential for ensuring food safety. Soil pollution from industrial and agricultural practices has serious implications for crop quality, as the ingestion of HM-laden food represents a major health risk. Likewise, sediments present three main exposure pathways: ingestion, inhalation, and skin contact (Miletic *et al.*, 2023). Humans may be exposed during recreational activities, occupational engagements or through residential proximity to contaminated areas. Human exposure to heavy metals (HMs) present in sediments also occurs through the consumption of aquatic organisms (Miletic *et al.*, 2023). HMs encompass both essential elements for mammalian physiology, such as Cr, Cu, Ni, and Zn, and those that are toxic even at low concentrations, including As, Cd, Hg, and Pb. However, even metals that are vital in trace amounts can become highly toxic and cause severe health complications when present in excessive concentrations within the human body (Pecina *et al.*, 2021). Exposure to elevated levels of HMs can result in damage to various organs, and long-term exposure has been associated with an increased risk of cancer development. Once inside the cell, HMs influence the redox balance, thereby interfering with intracellular biochemical processes (Miletic *et al.*, 2023). Several specific health disorders have been attributed to particular heavy metals. For example, high Cr exposure is linked to respiratory cancers; As has been associated with cognitive impairments in children, as well as dermatological and hepatic disorders (Fan *et al.*, 2022); Cd exposure may lead to osteoporosis, lung carcinogenesis, and renal dysfunction; high levels of Ni are known to induce asthma, pulmonary fibrosis, and contact dermatitis; Pb adversely affects

neurological development in children, reproductive health (Bai *et al.*, 2020), and can damage the nervous, skeletal, and immune system; excessive intake of Cu is associated with anemia and gastrointestinal disturbances (Miletic *et al.*, 2023).

Heavy metals are naturally present in minute quantities within the Earth's crust. Elements are grouped by their environmental and technological roles. Elements such as O, Si, Al, Fe, Ca, Na, Mg, K, and Ti constitute the principal framework of soil composition and are relatively abundant. Other notable groups include nonmetals (H, C, N, O, F, P, S, Cl, Br, and I), precious metals (Au, Ag, Pt, Pd, Rh, Ru, Os, and Ir), rare earth elements (Sc, Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu), and radioactive elements (Th and U). Additionally, elements frequently assessed in health risk studies; Cd, Cr, Cu, Ni, Pb, Zn, As, Hg, Co, Mn, V, Fe, Sb, Mo, and Ba, are also included to depict their distribution across the Earth's crust (Miletic *et al.*, 2023).

The general abundance order of HMs in the Earth's crust is as follows: Al > Fe > Ti > Mn > Ba > Sr > V > Cr > Ni > Zn > Cu > Co > Sc > Pb > B > Sn > As > Mo > Sb > Cd > Hg > Se > Bi. The types and levels of HMs studied can vary depending on the pollution source and soil type; however, research predominantly focuses on Cd, As, Cr, Cu, Hg, Ni, Pb, and Zn due to their significant environmental and health impacts. Any activity contributing to HM release elevates their environmental concentrations (urRehman *et al.*, 2018). Therefore, identifying the origins of such pollution is crucial, as it aids in understanding the distribution patterns of HMs in the soil (Zhang *et al.*, 2021). These metals may originate from natural geological processes or be introduced through anthropogenic sources. Soil formation, or pedogenesis, is the primary process influencing HM presence in natural soils. In contrast, in urban settings, anthropogenic pollution predominates. This trend is particularly evident in industrialized urban regions around the world (Miletic *et al.*, 2023).

The primary natural source of HMs is the parent geological material, from which metals are naturally released. Other natural processes contributing to HM dispersion include volcanic eruptions, sedimentation in river systems, erosion, rock formation, and weathering. With ongoing industrialization and urbanization, the number and intensity of anthropogenic HM sources continue to rise. Common anthropogenic activities responsible for HM emissions include industrial operations, agricultural practices (particularly involving pesticides and fertilizers), mining, construction, vehicular emissions (including exhaust gases), combustion of coal and other fuels, and improper disposal of sewage and industrial waste (Miletic *et al.*, 2023). Sediment contamination remains a pressing environmental issue, as many human activities generate substantial quantities of waste that can eventually deposit into aquatic sediments (Amin *et al.*, 2021).

## **2.1. Trends in the field of health risk assessment of HMs in soil and sediment**

Monte Carlo simulations were once used in evaluating risks associated with heavy metals from 1996 to 2022. The year 2023 was excluded from the analysis due to incomplete data. The period between 1996 and 2003 marks the initial phase of scholarly engagement in health risk assessment linked to heavy metals in soil and sediment (Miletic *et al.*, 2023). During this early stage, annual publication numbers remained below 50, indicating a nascent interest as researchers were beginning to explore the field. A noticeable rise in both publications and citations occurred after 2003 and persisted through 2021, reflecting an almost exponential trend (Miletic *et al.*, 2023). A minor decline was recorded in 2011; however, interest resumed its upward trajectory in subsequent years. By early 2023, projections indicated renewed growth in publications and citations, with the end-of-year figures expected to surpass those from 2021 and 2022. According to WoS data, a total of 10,911 articles had been published by 25 May 2023 on

this subject. A keyword-based literature review revealed that most researchers initially relied on deterministic models to assess human health risks associated with HMs in soil (Jiang *et al.*, 2021; Yan *et al.*, 2021). Recently, the application of probabilistic approaches has gained prominence. Some studies integrate both deterministic and probabilistic methodologies (Liu *et al.*, 2023), while others exclusively adopt the probabilistic model, considering it more succinct and advanced (Yang *et al.*, 2022). There has been a steady increase in publications utilizing Monte Carlo Simulation (MCS) for probabilistic health risk assessments of HMs in soil. Since 2002, the adoption of MCS has expanded, although with some fluctuations. Notable decreases occurred in 2010 and 2011, followed by a sharp rise in 2012, and subsequent declines between 2013 and 2015 (Miletic *et al.*, 2023).

## **2.2. Health risk assessment**

The evaluation of potential human health risks posed by contaminated soil or sediment is commonly referred to in the literature as human health risk assessment (HHRA), human health risk (HHR), or health risk assessment (HRA) (Miletic *et al.*, 2023). This process involves several critical steps. The initial phase entails identifying and characterizing hazards that may adversely impact human health. Since heavy metals are typically the principal pollutants in soil and sediment, most health risk evaluations focus on these contaminants (Raj *et al.*, 2022). For each metal, there exists a specific intake threshold beyond which adverse health effects may arise. Accordingly, it is essential to establish the concentration of metals that may lead to such outcomes. This assessment also requires knowledge of exposure parameters, including frequency, duration, and the exposure pathways involved. There are three primary routes of exposure: ingestion, inhalation, and dermal absorption (Miletic *et al.*, 2023). Ingestion refers to the unintentional swallowing of small soil particles. Inhalation involves breathing in fine soil or

sediment particles contaminated with heavy metals. Dermal exposure occurs through direct skin contact with polluted soil. The final phase of health risk assessment is the characterization of risk, which integrates the exposure data to estimate potential health outcomes. Individuals across all age groups may be affected through these pathways; however, assessments are generally categorized into adults and children (Kan *et al.*, 2021). The adult category encompasses both males and females, utilizing a standardized set of exposure parameters. Health effects linked to HMs are typically classified as carcinogenic or non-carcinogenic. Consequently, risk assessments generally include both types. While some studies focus solely on non-carcinogenic outcomes, the majority evaluate both non-carcinogenic and carcinogenic risks (Miletic *et al.*, 2023). Non-carcinogenic risk is quantified using the Hazard Index (HI), whereas carcinogenic risk is represented by the Total Carcinogenic Risk. These indices provide valuable insight into the degree of contamination and its potential effects on human health. Based on the values of HI and TCR, the level of threat posed by soil or sediment contaminants can be classified and quantified (Miletic *et al.*, 2023).

### **2.3. Average daily dose**

An essential step in both carcinogenic and non-carcinogenic health risk assessments is the computation of the daily intake of heavy metals (HMs) from contaminated soil or sediment. This value forms the basis for subsequent calculations, including final risk characterization. Researchers typically account for three main exposure pathways; ingestion, inhalation, and dermal absorption (Miletic *et al.*, 2023). However, since inhalation generally contributes the least to overall risk, some studies have concentrated solely on ingestion, or on both ingestion and dermal contact (Zhou *et al.*, 2018). The term used to describe daily exposure varies across studies. It is commonly referred to as chronic daily intake (CDI), average daily intake (ADI), or

most frequently, average daily dose (ADD). Less frequently used terms include D, daily intake of metals (DIM), and Exp. Despite terminological differences, these all denote the same concept: the estimated daily amount of heavy metals absorbed through various exposure routes (Miletic *et al.*, 2023). Some researchers have chosen to separately quantify daily intake for carcinogenic and non-carcinogenic outcomes. In such cases, ADD refers to non-carcinogenic exposure, while LADD (lifetime average daily dose) is used for carcinogenic risk estimation (Cui *et al.*, 2020). Several studies do not isolate the daily dose equations, instead integrating them directly into the hazard index (HI) or total carcinogenic risk (TCR) formulas (Zhou *et al.*, 2022). A term like ADD<sub>total</sub> may also be found, which aggregates the ADD values from all three pathways. Various terminologies are used for ingestion, including “ing”, “oral”, “uptake”, “ingestion”, “ingest”, and “soil ingestion”. For inhalation, “inh” is most typical, although “inhale” and “inhalation” are also used. Regarding dermal exposure, common terms include “der”, “skin”, “dermal contact”, “derm”, and “dermal” (Miletic *et al.*, 2023).

#### **2.4. Carcinogenic risk**

Carcinogenic risk reflects the potential of heavy metals in soil or sediment to cause cancer in exposed individuals. This risk is evaluated using two metrics: carcinogenic risk (CR) and total carcinogenic risk (TCR). The TCR value specifically indicates the cumulative potential health threat posed by long-term exposure to carcinogenic elements. Acceptable or tolerable risk thresholds range between  $1 \times 10^{-6}$  and  $1 \times 10^{-4}$ . A CR or TCR value below  $10^{-6}$  is generally considered negligible, whereas a value exceeding  $10^{-4}$  suggests an unacceptably high risk (Zhou *et al.*, 2022).

In addition to this conventional classification, some studies provide more nuanced categorizations, while others offer only partial categorization or none at all. Like non-carcinogenic risk, both CR and TCR are dimensionless values. The terminology “CR” and “TCR” is widely adopted in the literature, although some studies use only CR (Miletic *et al.*, 2023). Alternative terms include risk, CR and CRT, CR and LCR, TCR alone, CR and TR, ILCR and ILCRt, RI and ILCR, (RI) risk, RI, R, cancer risk and LCR, and CR, risk, and total carcinogenic risk (Karimi *et al.*, 2020).

## **2.5. Ingestion rate (IngR)**

The ingestion rate denotes the quantity of soil or sediment ingested by an individual over a defined time, typically per day, and is expressed in  $\text{mg}\cdot\text{day}^{-1}$  or  $\text{mg}\cdot\text{d}^{-1}$ . This value is typically higher in children than in adults, reflecting their greater likelihood of soil or sediment contact and accidental ingestion. Some studies, however, use identical ingestion rates for both age groups. A majority of studies, assuming residential exposure scenarios ( $\text{EF} = 350$ ), adopt ingestion rates of  $200 \text{ mg}\cdot\text{day}^{-1}$  for children and  $100 \text{ mg}\cdot\text{day}^{-1}$  for adults. However, lower values are occasionally used: for children, 100, 60, 50, 30, and 20; and for adults, 50, 30, 20, and 10 (Miletic *et al.*, 2023).

## **2.6. Inhalation rate (InhR)**

The inhalation rate quantifies the volume of air (in  $\text{m}^3$ ) that contains soil or sediment particles inhaled by a person daily. It is expressed as  $\text{m}^3\cdot\text{day}^{-1}$  or  $\text{m}^3\cdot\text{d}^{-1}$ . This metric is used exclusively in the inhalation exposure equation. For children, inhalation rates typically range between 7.3 and 16.57 and occasionally 7.3, 8.1, 9.3, 10, 7.65, and 16.57. For adults, reported values span from 12.8 to 20, with the most common value being 20 (Miletic *et al.*, 2023).

## 2.7. Exposure frequency (EF)

Exposure frequency refers to the number of days in a year an individual is exposed to contaminated soil or sediment. This parameter is commonly expressed in several unit forms, such as  $\text{day}\cdot\text{year}^{-1}$ ,  $\text{days}\cdot\text{year}^{-1}$ ,  $\text{d}\cdot\text{a}^{-1}$ ,  $\text{d}\cdot\text{year}^{-1}$ ,  $\text{days}\cdot\text{y}^{-1}$ ,  $\text{day}\cdot\text{a}^{-1}$ ,  $\text{d}\cdot\text{yr}^{-1}$ ,  $\text{day}\cdot\text{yr}^{-1}$ , and  $\text{d}\cdot\text{years}^{-1}$ . It is frequently abbreviated as EF (Miletic *et al.*, 2023). Researchers typically assume equivalent exposure durations for both children and adults, given that both age groups are considered to have similar outdoor activity patterns throughout the year. Accordingly, a value of 350 days per year is most frequently used. This value is slightly below the total number of days in a year to account for periods when individuals may not be exposed. In some cases, differentiated land-use categories such as industrial, recreational, agricultural, and forest areas are analyzed, leading to values such as 262.5, 345, 312, 180, and 365 (Adimalla *et al.*, 2020; Chen *et al.*, 2020).

## 2.8. Exposure duration (ED)

The exposure duration quantifies the length of time, measured in years, over which individuals are assumed to come into contact with polluted soil or sediment. Although generally referred to as “exposure duration” across studies, an exception is noted in Bernardo *et al.* (2022), where the term “exposure period” was used. The standard abbreviation is ED. Units of measurement vary, including year, years, a, and yr (Obiri-Nyarko *et al.*, 2021). For children, a value of 6 years is widely accepted as representing the average age group considered at risk (Sarim *et al.*, 2022). For adults, durations range from 20 to 35 years, with 24 years being the most frequently adopted followed by 30 years. Less common durations include 20, 26, and 35 years (Miletic *et al.*, 2023).

## 2.9. Particulate emission factor (PEF)

The particulate emission factor is a parameter applied exclusively in the inhalation exposure model. It quantifies the amount of particulate matter, in  $\text{m}^3$ , emitted from 1 kg of contaminated soil or sediment. Typically designated as PEF, this parameter was referred to as EF<sub>p</sub> in only one study by Alsafran *et al.* (2021). Nearly all studies employed a uniform value of  $1.36 \times 10^9 \text{ m}^3 \cdot \text{kg}^{-1}$  for both adults and children. However, a few studies reported slightly lower values, such as  $1.32 \times 10^9$  (urRehman *et al.*, 2018; Chen *et al.*, 2022). Terminological variations include “emission factor”, “dust emission factor”, “particulate emission factor”, and “inhalation factor for emission particulates”, though “particulate emission factor” is most widely accepted (Miletic *et al.*, 2023).

## 2.10. Skin surface area (SA)

Skin surface area, used in dermal exposure assessments, refers to the contact area of the skin in square centimeters ( $\text{cm}^2$ ) that comes into direct contact with contaminated soil or sediment. Numerous designations exist, such as “skin surface area”, “skin surface area available for contact”, “surface area of the skin that contacts the PTEs”, “exposed skin surface area”, and “skin area exposed to soil contact”. Units include  $\text{cm}^2$ ,  $\text{cm}^2 \cdot \text{day}^{-1}$ , and  $\text{cm}^2 \cdot \text{d}^{-1}$  (Miletic *et al.*, 2023). It is most often abbreviated as SA, but other acronyms like ESA, ESAs, and Askin are also employed. Children's SA values range from 899 to 2800  $\text{cm}^2$ , including 2373, 2800, 1600, 2448, 899, and 2848.01. Adult SA values range between 1701 and 6032  $\text{cm}^2$ , with frequently used values including 5800, 5373.99, 1701, 5075, 4350, 5700, and 6032 (Miletic *et al.*, 2023). The most commonly adopted values are 2800 for children and 5700 for adults, though these are not always paired consistently in all studies (Miletic *et al.*, 2023).

### **2.11. Adherence factor (AF)**

The adherence factor estimates the quantity of heavy metals that stick to the skin upon contact and is featured in the dermal contact equation. It is usually denoted as AF, but other variants include SL, SAF, AFs, and AFsoil. The U.S. Environmental Protection Agency (USEPA) recommends values of 0.2 for children and 0.07 for adults, although alternative values have been reported. For children, these include 0.65, 0.07,  $1 \times 10^{-6}$ , and  $2 \times 10^{-6}$ . For adults, values include 0.22, 1, 0.49,  $2 \times 10^{-7}$ , 0.2, 0.3745, and 0.7 (Miletic *et al.*, 2023). Terminological diversity is notable, with expressions such as “adherence factor”, “skin adherence factor”, “soil-to-skin adherence factor”, and “skin adhesion”. Units vary considerably, including  $\text{mg}\cdot\text{cm}^{-2}\cdot\text{day}^{-1}$ ,  $\text{mg}\cdot\text{cm}^{-2}$ ,  $\text{mg}\cdot\text{cm}^{-2}\cdot\text{h}^{-1}$ ,  $\text{mg}\cdot\text{cm}^{-2}\cdot\text{event}^{-1}$ , and  $\text{kg}\cdot\text{cm}^{-2}\cdot\text{day}^{-1}$  (Miletic *et al.*, 2023). The USEPA prescribes  $\text{mg}\cdot\text{cm}^{-2}\cdot\text{event}^{-1}$  or  $\text{mg}\cdot\text{cm}^{-2}\cdot\text{day}^{-1}$ , with dimensional analysis indicating that when AF is expressed in  $\text{mg}\cdot\text{cm}^{-2}\cdot\text{day}^{-1}$ , the ADD unit becomes  $\text{mg}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$  (Miletic *et al.*, 2023).

### **2.12. Dermal absorption factor (ABS)**

The dermal absorption factor measures the fraction of heavy metals absorbed through the skin and appears exclusively in the dermal contact model. Descriptions include “dermal absorption factor”, “absorption factor”, “contact factor”, “skin absorption factor”, “dermal absorption fraction”, and “skin adsorption coefficient” (Fan *et al.*, 2022). This parameter is dimensionless and is often labeled as unitless, nondimensional, or simply left blank. The abbreviation ABS is most prevalent, though ABF, DA, and DAF are also used. Two main usage patterns are evident: (1) a consistent value of 0.001 across all metals and age groups for both carcinogenic and non-carcinogenic risks; and (2) metal-specific values, e.g., 0.03 for arsenic and 0.001 for others; or variable values based on metal type. Among these, the first approach is the most frequently adopted (Miletic *et al.*, 2023).

### 2.13. Body weight (BW)

Body weight is an important variable in the ADD calculation because it significantly influences how much of a contaminant dose affects the human body. This value is expressed in kilograms and abbreviated as BW, although EBW, ABW, and BWA are also used. The standard weight for children is generally 15 kg, while 70 kg is the commonly used figure for adults. However, considerable variability exists: for children, weights reported include 15.9, 6, 22, 16.2, 20, 19.6, 24.7, 29.3, 22.5, 18.6, 19.2, and 29; and for adults, values include 80, 55.9, 56.9, 60, 68.4, 61.8, 57, 62.5, 56.8, 60.6, 62.57, 63, 62, and 59 (Miletic *et al.*, 2023).

### 2.14. Reference dose (RfD)

The reference dose (RfD) is defined as an estimated threshold of daily exposure to heavy metals (HMs) that is not anticipated to pose adverse health effects over a human lifetime. Each metal is assigned a unique RfD value. This parameter is crucial in the assessment of non-carcinogenic risk and is typically expressed in units identical to those used for average daily dose (ADD), namely  $\text{mg}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$  (Miletic *et al.*, 2023). Some studies also adopted the same unit notation using alternate formatting styles. For the inhalation exposure route, a few researchers distinguished RfD units as  $\text{mg}\cdot\text{m}^{-3}$  to reflect the different exposure medium (Wang *et al.*, 2022). As with ADD, RfD values are delineated according to the three major exposure pathways: ingestion, inhalation, and dermal contact. Numerous comparative assessments of RfD values across these routes have been documented for a wide array of HMs, including cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), mercury (Hg), arsenic (As), manganese (Mn), cobalt (Co), vanadium (V), iron (Fe), molybdenum (Mo), barium (Ba), and antimony (Sb). Due to variability in reported values across studies, the most frequently cited and widely accepted RfD values were generally adopted. Ingestion-related RfDs for many metals are

available through the U.S. Environmental Protection Agency's Integrated Risk Information System (USEPA IRIS). Among the metals investigated, Cd, As, Cr, Cu, Ni, Pb, and Zn are the most frequently evaluated in risk assessments. Fewer studies have addressed Hg, Mn, and Co, while data on V, Mo, Ba, Fe, and Sb remain relatively scarce in the literature (Miletic *et al.*, 2023).

### **2.15. Cancer slope factor (CSF)**

The cancer slope factor (CSF) serves as a critical parameter in carcinogenic risk assessment and acts as the carcinogenic counterpart to the RfD. It reflects the probability of developing cancer per unit of contaminant intake and is generally expressed in units of  $\text{kg}\cdot\text{day}\cdot\text{mg}^{-1}$  (Heidari *et al.*, 2021). However, inconsistencies in CSF unit notation have been reported. While the correct formulation ( $\text{kg}\cdot\text{d}\cdot\text{mg}^{-1}$  or  $\text{kg}\cdot\text{day}\cdot\text{mg}^{-1}$ ) dominates the literature, some researchers have erroneously expressed the CSF in units such as  $\text{mg}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$  or  $\text{mg}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$ , which is dimensionally inaccurate. A few sources omitted unit specification entirely or described the CSF as unitless (Wang *et al.*, 2019). To preserve the unit consistency and dimensionless nature of carcinogenic risk (CR) and total carcinogenic risk (TCR), the CSF must be expressed as the reciprocal of the ADD unit, i.e.,  $\text{kg}\cdot\text{day}\cdot\text{mg}^{-1}$ . In the context of inhalation, some studies used  $\text{m}^3\cdot\text{mg}^{-1}$  for CSF to align with inhalation-specific ADD units. CSF values vary across metals and exposure routes. While the abbreviation CSF is most widely accepted and aligns with USEPA terminology, alternate notations such as SF also appear in academic literature. In contrast to RfD values, which exist for most metals, CSFs are available only for those HMs classified as carcinogenic. The metals most commonly identified as carcinogenic include Cd, Cr, Ni, Pb, and As (Miletic *et al.*, 2023). Less frequently, copper (Cu) and cobalt (Co) have also been considered carcinogenic by some authors. Substantial variability exists in

reported CSF values across different studies. In some instances, authors derived new CSF values, particularly for dermal exposure scenarios (Miletic *et al.*, 2023).

## **2.16. Review of related literature**

Saleem *et al.* (2014) conducted a comprehensive assessment of human health risks linked to heavy metal contamination in surface soils around Mangla Lake, Pakistan. Their study focused on evaluating both non-carcinogenic and carcinogenic risks from metals including cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), lead (Pb), and zinc (Zn), considering multiple exposure routes such as oral ingestion, dermal contact, and inhalation of soil particulates. Emphasis was placed on the vulnerability of children, who are more susceptible to soil-associated health hazards due to their frequent hand-to-mouth activities and closer proximity to the ground. The concentration of metals in surface soil, measured during both summer and winter, revealed seasonal variations. In the summer season, the descending order of metal concentrations was Fe (4038 mg/kg), Mn (394 mg/kg), Zn (40 mg/kg), Pb (17 mg/kg), Cr (21 mg/kg), Cu (15 mg/kg), and Cd (1.3 mg/kg). In winter, the trend slightly differed: Fe (3673 mg/kg), Mn (407 mg/kg), Zn (30 mg/kg), Cr (26 mg/kg), Pb (26 mg/kg), Cu (14 mg/kg), and Cd (1.8 mg/kg). These findings indicated elevated metal concentrations when compared with guideline values and previous reports, suggesting a significant degree of environmental contamination. Spatial distribution analysis further revealed uneven metal dispersion around the lake, likely influenced by both natural and anthropogenic sources. To investigate the sources of contamination, the researchers employed correlation analysis and principal component analysis (PCA), which pointed toward significant anthropogenic inputs, particularly for Cd, Pb, and Cr. The pseudo-total metal contents, extracted using aqua regia digestion, were used to approximate the bioavailable fractions of these elements. Bioavailability rankings remained consistent across

both seasons, following the order: Cd > Pb > Cr > Zn > Cu > Fe > Mn. This approach allowed the researchers to refine their risk assessment by focusing on the biologically accessible metal fractions, which are more relevant for human exposure. In terms of health risk evaluation, the study found that although the calculated non-carcinogenic hazard index (HI) and carcinogenic risk values generally remained below critical thresholds (HI < 1.0 and cancer risk < 1.0E-06), Cd, Pb, and Cr exhibited relatively higher contributions to overall risk, especially Cr, which caused the cancer risk level to exceed the recommended safety threshold for adults. This underscores the importance of using bioavailability-adjusted concentrations in risk assessments for a more accurate reflection of human exposure potential.

Wang *et al.* (2020) investigated the potential health impacts associated with heavy metal contamination in a rural region of Guangxi, China, which had been affected by extensive mining activities. The study focused on evaluating the non-carcinogenic health risks posed by seven heavy metals (HMs) to children, who are considered a particularly vulnerable population due to their heightened exposure and physiological sensitivity. The risk assessment considered both environmental exposure routes and dietary intake through locally cultivated sugarcane juice. Exposure pathways assessed included inhalation, dermal contact, oral ingestion of contaminated soil, and consumption of sugarcane juice grown in the contaminated area. The comparative analysis of exposure routes revealed that the ingestion of sugarcane juice posed the greatest health risk, followed by non-dietary oral intake, dermal absorption, and finally, inhalation of soil particles. This hierarchy emphasized the significant role of dietary exposure in heavy metal risk assessments, particularly in agrarian communities dependent on local produce. Regarding non-carcinogenic health risks, the study found that chromium (Cr) and cadmium (Cd) presented the highest risks through sugarcane juice consumption, while arsenic (As) and lead (Pb) were the

dominant contributors to non-dietary exposure-related risks. These findings highlighted the complex and varied toxicity profiles of heavy metals depending on the route of human exposure. To enhance the reliability of the health risk assessment, the researchers developed a regression-based model that linked the hazard index (HI) of heavy metals to the ratio of soil HM concentrations to their corresponding total reference doses. This approach enabled the integration of environmental contamination levels with biological susceptibility indicators, providing a more holistic understanding of risk. The model demonstrated that non-dietary risk was significantly associated with both the magnitude of soil contamination and the physiological sensitivity of individuals, as indicated by the total daily reference doses for each metal.

Gupta and Gupta (2023) applied an integrated risk assessment methodology to evaluate chronic human exposure to heavy metals in a riverine ecosystem. The study utilized both deterministic and probabilistic approaches, specifically incorporating Monte Carlo simulations alongside sensitivity analysis, to quantify chronic daily intake (CDI) and estimate associated human health risks. These assessments accounted for both carcinogenic and non-carcinogenic outcomes across multiple exposure pathways, including contact with water and sediment. Analytical findings demonstrated that heavy metal concentrations were generally higher in sediments than in water. The descending order of concentrations in sediment was  $Fe > Mn > Sr > Zn > Cr > Cu > Cd$ , whereas water samples followed the order  $Fe > Zn > Cr > Sr > Mn > Cu > Cd$ . This difference in distribution emphasizes the sediment's greater potential to act as a long-term reservoir for heavy metals. The risk analysis revealed that chromium (Cr) and cadmium (Cd) presented notably higher carcinogenic risk levels in sediment compared to water. Specifically, the carcinogenic risk values for Cr and Cd in sediment were  $5.06E-02$  and  $5.98E-04$ , significantly exceeding those observed in water ( $9.08E-04$  and  $8.97E-05$ , respectively).

Moreover, the 95th percentile values of total cancer risk (TCR) derived from probabilistic modeling showed that sediment-related exposure posed considerably greater risks. For adults and children, the TCR values from sediment were approximately 22 and 143 times higher, respectively, than those from water, indicating that sediment poses a substantially greater health hazard, especially for younger individuals. In terms of non-carcinogenic outcomes, the study found that the overall hazard index (OHI) for both sediment and water greatly surpassed the United States Environmental Protection Agency (USEPA) safety threshold of 1.0. For sediment, OHI values reached  $1.26E+02$  in adults and  $1.11E+03$  in children, while for water, the values were  $3.26E+00$  for adults and  $9.85E+00$  for children. These values indicate a significant level of potential chronic health risk, particularly for children who are more vulnerable due to physiological and behavioral factors. Sensitivity analysis further highlighted that metal concentration was the most critical input variable influencing health risk estimates. This insight underscores the need for accurate environmental monitoring in risk assessment models. The study recommended the adoption of reasonable maximum exposure (RME) estimates to improve risk prediction and provide practical guidance for environmental health professionals, researchers, and policy stakeholders involved in managing heavy metal contamination.

Bhatti *et al.* (2020) conducted an extensive investigation into the human health risks associated with the consumption of staple crops cultivated on soils contaminated with metal(loid)s in the riverine regions of Punjab, India, particularly around the Beas and Sutlej rivers. The study focused on wheat and rice, two primary food sources in the region, assessing the concentrations of various metal(loid)s including arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), selenium (Se), and zinc (Zn). Among the detected elements, levels of As, Cd, Cr, Ni, and

Pb in both wheat and rice samples exceeded the maximum allowable limits set by international standards such as the Food and Agriculture Organization/World Health Organization (FAO/WHO) and the European Union (EU). These exceedances suggested significant contamination of the soil-plant system, raising serious concerns about food safety and chronic health outcomes for consumers. Health risk assessments revealed that arsenic posed the greatest risk, followed by cadmium, copper, iron, manganese, and lead. Both non-carcinogenic and carcinogenic risks were evaluated for each metal(loid) independently, as well as cumulatively. The combined non-carcinogenic risk, expressed as the hazard index (HI), ranged between 3.49 and 15.94, which far exceeded the generally accepted threshold value of 1.0. Similarly, the total carcinogenic risk index ranged from  $8.30 \times 10^{-4}$  to  $131.62 \times 10^{-4}$ , surpassing the regulatory benchmark of  $1.0 \times 10^{-4}$ . These elevated values clearly indicated that residents consuming wheat and rice grown in the studied areas were at significant risk of both non-cancer and cancer-related health effects. Although the primary exposure route examined in this study was dietary, the results highlight the broader implications of soil contamination, including the potential for secondary exposure through inhalation of dust from metal(loid)-laden soils. This has direct relevance to inhalation-based risk assessments, particularly in agrarian environments where soil particulates are easily resuspended into the atmosphere during farming or dry seasons. The authors concluded that urgent remediation measures are needed to reduce the metal(loid) concentrations in crops and thereby mitigate the long-term health impacts on local populations. The findings support the growing need for integrated environmental and health risk management strategies in regions affected by heavy metal contamination.

Praveena *et al.* (2015) investigated the extent of heavy metal contamination in urban soils within Klang District, Malaysia, and evaluated the associated human health risks. The study

assessed both carcinogenic and non-carcinogenic risks in adults and children by examining the concentrations and bioavailability of various heavy metals in soil. The research also aimed to identify the most critical contaminants and dominant exposure pathways in the urban environment. The mean concentrations of bioavailable heavy metals in the soil were observed in the following decreasing order: iron (Fe) > zinc (Zn) > copper (Cu) > cobalt (Co) > cadmium (Cd) > lead (Pb) > chromium (Cr). Specifically, mean levels were recorded as 6.65 mg/kg for Fe, 5.61 mg/kg for Zn, 2.96 mg/kg for Cu, and lower values for Co, Cd, Pb, and Cr. Notably, the maximum concentrations of Cd (0.64 mg/kg), Cu (52.14 mg/kg), and Pb (9.18 mg/kg) surpassed standard soil quality guideline thresholds, indicating elevated contamination levels in some urban soil samples. The carcinogenic risk assessment revealed that cadmium (Cd), chromium (Cr), and lead (Pb) all exceeded the benchmark incremental lifetime cancer risk level of  $1.0 \times 10^{-5}$ . This suggests that prolonged exposure to these metals through soil contact may pose a potential cancer risk to both adults and children residing in the area. In contrast, the non-carcinogenic risk analysis showed that the hazard index (HI) values for all evaluated metals (including Co, Cr, Cu, Pb, and Zn) were below the critical value of 1.0. Therefore, under current exposure conditions, there is no significant indication of non-carcinogenic health risks for the population. Among the contaminants assessed, Cd was identified as the most hazardous metal, not only due to its elevated concentration but also because of its high carcinogenic potential. The study also ranked exposure pathways in order of significance. For both carcinogenic and non-carcinogenic risks, the primary route of exposure was ingestion, followed by dermal contact and then inhalation. Although inhalation posed the least contribution to overall risk in this context, its inclusion remains important in comprehensive risk assessments, particularly in urban environments where resuspension of contaminated soil particles into the air can occur.



## CHAPTER THREE

### MATERIALS AND METHOD

#### 3.0. REGIONAL GEOLOGY

Etsako-West Local Government Area is located in the northern part of Edo State, Nigeria, approximately between latitudes  $6^{\circ} 45' N$  and  $7^{\circ} 35' N$  and longitudes  $5^{\circ} 55' E$  and  $6^{\circ} 45' E$ . Regionally, it forms part of the southwestern segment of the Nigerian Basement Complex, a major component of the Pan-African Trans-Saharan mobile belt that developed through the collision and suturing of the West African and Congo cratons (Rahaman, 1988; Dada, 2008). This tectonic domain is characterized by complex Precambrian crystalline rocks and subordinate Cretaceous sedimentary sequences. The basement complex is dominated by migmatite-gneiss complexes, quartzites, mica schists, and granitic intrusives that record multiple tectonothermal episodes (Rahaman, 1988; Ajibade and Woakes, 1989). These rocks have undergone repeated phases of high- to medium-grade metamorphism, deformation, and magmatism associated with the Pan-African orogeny, dated at approximately  $600 \pm 150$  Ma (Dada, 2008). The Etsako-West metamorphic domain, particularly around Igarra, is a key part of Nigeria's Migmatite – Gneiss Complex within the Pan-African mobile belt. (Udi *et al.*, 2023) documented syn- to late-tectonic intrusion of Pan-African granitoids (circa  $600 \text{ Ma} \pm 150 \text{ Ma}$ ) that reportedly reactivated pre-existing E – W fault systems. (McCurry, 1971) described two primary deformation phases:  $D_1$  (E – NE to W – SW) and  $D_2$  (N – S), accompanied by migmatization, granite emplacement, and subsequent fracturing and faulting. The regional lithostratigraphy comprises migmatitic gneisses, schist belts, and granitoids. (Ajibade *et al.*, 1987) showed that syn-tectonic granites intrude both

older basement and supracrustal cover, indicating significant crustal reworking. Regional geology further reflects pervasive foliation, isoclinal folding, and metamorphic conditions ranging from greenschist up to amphibolite and localized granulite facies, especially where partial melting occurred. Stress analyses of the Igarra Schist Belt by (Udinmwun, 2017) identified two deformation episodes: first NE – SW, then E – W with the E – W trend being dominant and indicative of ductile to brittle deformation. Metamorphic pressure – temperature profiles across the Benin – Nigerian Shield corroborate a metamorphic gradient — from middle greenschist (approx. 400 ° C) to upper amphibolite facies (680 – 750 ° C), highlighting the region’s significant tectonothermal evolution during the Pan-African event (Ephraim *et al.*, 2008).

### **3.0.1. Migmatite-gneiss formations**

At the site scale, exposures in Etsako-West show that the migmatite-gneiss complex forms the principal basement unit. These rocks are typically banded and consist of alternating felsic and mafic layers (Obasi *et al.*, 2020). Petrographic descriptions from nearby mapped localities report quartz, K-feldspar and plagioclase in the felsic bands, and biotite and hornblende in the mafic bands. Locally the gneisses grade into migmatites with leucosome veins and granite injections, indicating partial anatexis during high-grade metamorphism. Supracrustal packages comprising schist, quartzite and calc-silicate rocks are commonly found adjacent to these gneissic bodies, demonstrating lateral juxtaposition of sedimentary protoliths and basement rocks during deformation (Adegbuyi *et al.*, 2018; Rahaman, 1988).

### **3.0.2. Granitoid intrusions**

Pan-African granitoids and associated porphyritic or coarse-grained granites are common intrusive phases in the Etsako-West basement. Field relations indicate that many granitoid bodies were emplaced syn- to post-tectonically, producing sharp intrusive contacts, country-rock assimilation, and local development of granitic gneiss through deformation and metamorphism. Geochemical and regional petrogenetic studies of Pan-African granites in Nigeria interpret these intrusions mainly as crustal melts produced by tectonothermal reworking during the Pan-African orogeny (Sanni *et al.*, 2023; Oyewole and Ofuyah, 2017).

### **3.0.3. Mineralogical composition**

the metacarbonate deposits of Enwan, Bekuma, and Ekpedo display a distinct mineralogical composition. Analyses reveal that the rocks at Enwan contain an average of 96.4% calcium carbonate and 3.6% magnesium oxide, while those from Ekpedo contain 58.5% calcium carbonate and 41.5% magnesium oxide. The Bekuma deposits hold 77.35% calcium carbonate and 13.1% magnesium oxide. Across all three locations, the primary minerals are calcite and dolomite, with calcite as the dominant phase. Additional minerals present include quartz, plagioclase, and muscovite, which occur in smaller proportions (Omotehinse and Taiwo, 2022; Nweke *et al.*, 2024).

### **3.0.4. Hydrogeological and structural controls on groundwater**

Hard-rock aquifers in Etsako-West are strongly controlled by secondary permeability associated with fractures, weathered zones, and structural lineaments. Remote sensing and lineament mapping studies in Etsako-West demonstrate a network of linear features that correspond to faults and shear zones. These lineaments often localize groundwater occurrence and influence recharge pathways in otherwise low-porosity basement rocks (Salami *et al.*, 2024).

### **3.1. LOCAL GEOLOGY**

Imeke is a village in Etsako-West Local Government Area, Edo State, located at approximately 7.1321° N, 6.2027° E. The village lies within the rugged, ridge-dominated terrain that characterizes the Etsako-West domain. The area is part of the Precambrian Nigerian Basement Complex and sits within the Pan-African mobile belt produced by the Neoproterozoic collision and suturing of the West African and Congo cratons (Rahaman, 1988; Dada, 2008). Imeke is underlain by rocks of the Precambrian Basement Complex. The dominant lithologies of the Etsako-West region include migmatite-gneiss complexes, banded gneisses, schists and supracrustal sequences, subordinate quartzites, and various granitoid intrusions (Rahaman, 1988; Ajibade and Woakes, 1989).

### **3.2. MATERIALS**

The materials and equipment used in the study included 75 cl plastic sampling plates , portable calibrated meters, ultra-pure nitric acid (HNO<sub>3</sub>), ice-packed coolers, Atomic Absorption Spectrophotometer (AAS), analytical-grade stock solutions, standard laboratory glassware, distilled water, blanks, calibration standards for each metal, PPE, data analysis software, statistical software (SPSS).

### **3.3. METHODS**

#### **3.3.1 Sample Collection**

Ten (10) Soil samples were collected from Different depths and points across the study area. Prior to collection, each sampling container ( plastic plates) was thoroughly rinsed with clean water. In situ measurements of physicochemical parameters, including pH, electrical conductivity (EC), temperature, total dissolved solids (TDS), and dissolved oxygen (DO), were taken using portable, calibrated meters. All samples were acidified to pH < 2 with ultrapure nitric

acid (HNO<sub>3</sub>) to prevent metal precipitation and adsorption to container walls, then stored at 4 °C in ice-packed coolers and transported to the laboratory for heavy metal analysis.

### **3.3.2. Laboratory analysis**

The concentrations of target heavy metals: Lead (Pb), Cadmium (Cd), Chromium (Cr), Arsenic (As), Nickel (Ni), Zinc (Zn), Copper (Cu), and Iron (Fe) were determined using Atomic Absorption Spectrophotometry (AAS). Prior to measurement, the instrument was calibrated with standard solutions prepared from analytical-grade stock solutions (1000 mg/L) of each metal. Blanks and replicate analyses were used to ensure precision and accuracy. Detection limits were determined for each metal to validate analytical sensitivity. Parameters such as Total Dissolved Solids (TDS), Total Hardness, and Alkalinity were determined using standard titrimetric and gravimetric methods as outlined by (APHA, 2017).

### **3.3.3. Human Health Risk Assessment: Ingestion Pathway**

Human health risk assessment for heavy metals in groundwater was carried out in accordance with the United States Environmental Protection Agency (US EPA, 1989; 2004) guidelines, focusing on the ingestion exposure route. The methodology involved determining the Chronic Daily Intake (CDI), estimating the of non-carcinogenic risk (Hazard Quotient, HQ) and carcinogenic risk (CR) for identified heavy metals.

### **3.3.4. Chronic Daily Intake (CDI)**

The CDI through ingestion was determined using Equation (1):

$$CDI = C_w \times IR \times EF \times ED / BW \times AT$$

The variable  $C_w$  denotes the concentration of heavy metals in soil expressed in milligrams per Kilogram (mg/kg). The ingestion rate of soil is represented by  $IR$  and measured in Milligrams

per day (mg/day). *ER* refers to the exposure frequency in days per year, while *ED* indicates the exposure duration in years. Body weight is expressed as *BW* in kilograms (kg). The averaging time, denoted as *AT*, is calculated in days and differs depending on the type of effect considered: for non-carcinogenic effects, *AT* equals *ED*, whereas for carcinogenic effects, it is set at  $70 \times 365$  (Samaila *et al.*, 2024).

### 3.3.5. Ecological risks of heavy metals in soil

The ecological risk index (ERI) serves as an integrated measure for evaluating the potential ecological threats associated with heavy metal contamination in soil (Sharifi *et al.*, 2016). It is given as;

$$ERI = \sum_{i=1}^n T_i \times M_i / S_i$$

The parameter  $T_i$  represents the biological toxicity factor assigned to a specific heavy metal. The values of  $T_i$  are determined as  $Cu = Ni = Pb = Co = 5$ ,  $Mn = Zn = 1$ ,  $As = 10$ , and  $Cd = 30$  (Hakanson, 1980; Sharifi *et al.*, 2016). The ecological risk index (ERI) is categorized into levels of severity, namely: low risk when ERI is less than 110; moderate risk when ERI ranges from 110 to less than 200; considerable risk when ERI lies between 200 and less than 400; and very high risk when ERI equals or exceeds 400 (Sharifi *et al.*, 2016).

### 3.3.6. Health risks of Heavy metals in soil

The assessment of health risks followed the guidelines established by the United States Environmental Protection Agency (USEPA, 1989). In soil, exposure to heavy metals occurs primarily through inhalation, ingestion and dermal absorption (Kim *et al.*, 2004; Wu *et al.*, 2009). To evaluate these risks, both cancer risk (CR) and hazard quotient (HQ) were applied as key indicators (USEPA, 2016; Wu *et al.*, 2018a; Lv *et al.*, 2019).

### 3.3.7. Determination of non-carcinogenic risk

This assessment aims to measure the potential health implications arising from exposure to non-carcinogenic contaminants. The hazard quotient (HQ) is calculated by dividing the estimated daily exposure dose by the oral reference dose (RfD), with both expressed in milligrams per kilogram per day (mg/kg/day). An HQ value exceeding one indicates the likelihood of adverse health outcomes resulting from contact with the contaminant.  $HQ = ADD/RfD$

An HQ value greater than one signifies a potential for harmful health effects, while a value less than one indicates minimal risk. The average daily dose (ADD) was determined by considering multiple human exposure pathways, namely ingestion, inhalation, and dermal absorption (Zglobicki and Telecka, 2021). The associated risks were calculated using

$$ADD_{\text{ingestion}} = \frac{C \times R_{\text{ing}} \times EF \times ED}{BW \times AT} \times 10^{-6} \dots\dots\dots (1)$$

$$ADD_{\text{inhalation}} = \frac{C \times R_{\text{inh}} \times EF \times ED}{PEF \times BW \times AT} \dots\dots\dots (2)$$

$$ADD_{\text{dermal}} = \frac{C \times SA \times SL \times ABF \times EF \times ED}{BW \times AT} \times 10^{-6} \dots\dots\dots (3)$$

Therefore, the total ADD can be evaluated by adding the ADD dermal + ADD inhalation + ADD ingestion.

equations presented below:

Where C = Concentration of metal (µg/kg, mg/kg),  $R_{\text{ing}}$  = ingestion rate,  $R_{\text{inh}}$  = inhalation Rate, EF is Exposure Frequency (days/yr), SA = exposed skin area, ABF = the exposure duration (h/day), SL = the chemical-specific dermal permeability constant (cm/h), ED = Exposure Duration (yr), AT = Averaging Time (period over which exposure is averaged) (days), BW = Body Weight (kg).

The Hazard Index (HI) is utilized to evaluate the overall non-carcinogenic risk associated with concurrent exposure to multiple heavy metals detected in the analyzed samples. The HI is obtained by summing the individual Hazard Quotients (HQs) for each metal (Goumenou and Tsatsakis, 2019). The HQ represents the risk from a particular exposure pathway and is classified as  $HQ_{inh}$  for inhalation,  $HQ_{ing}$  for ingestion,  $HQ_{derm}$  for dermal contact, and  $HQ_t$  as the total hazard quotient from all exposure routes combined.

$$HQ_{ing} = CDI_{ing}/RFD_{ing}$$

$$HQ_{inh} = CDI_{inh}/RFD_{inh}$$

$$HQ_{derm} = CDI_{derm}/RFD_{derm}$$

### 3.3.8. Hazard index for children and adults

An HI value exceeding one indicates a potential risk to human health, while values less than one are typically regarded as posing minimal concern. The hazard index is determined using the following formula:

$$HI = \frac{C_{metal} \times IR \times EF \times ED}{RfD \times BW \times AT}$$

- $HI < 1$  implies an insignificant health risk,
- $1 \leq HI < 4$  suggests the possibility of risk, and
- $HI > 4$  indicates a high level of non-carcinogenic health risk.

### 3.3.9. Carcinogenic risk assessment

Carcinogenic risk (CR) was assessed following the method outlined by (Maeaba *et al.*, 2019) to estimate the lifetime probability of developing cancer due to exposure to carcinogenic heavy

metals such as arsenic (As), nickel (Ni), lead (Pb), cadmium (Cd), cobalt (Co), and chromium (Cr). The subsequent equations were employed to calculate carcinogenic risk for the various exposure pathways:

$$CR = ADD \times SF \dots\dots\dots(1)$$

Where CR= Cancer risk, ADD = Average daily dose and SF = Cancer slope factor

$$TCR = \sum CR = CR_{ing} + CR_{inh} + CR_{derm} \dots\dots\dots(2)$$

TCR represents the Total Carcinogenic Risk, while CR denotes the individual Carcinogenic Risk. Based on established guidelines, a TCR value between  $1 \times 10^{-6}$  and  $1 \times 10^{-4}$  is regarded as acceptable, indicating no significant risk to human health (Itam *et al.*, 2024). Conversely, values equal to or greater than  $1 \times 10^{-3}$  may reflect an increased likelihood of cancer occurrence over a lifetime of exposure.

### 3.3.10. Statistical Analysis

The dataset, including all estimated parameters, was analyzed statistically to compute the mean and standard deviation. This was performed using the Statistical Package for the Social Sciences (SPSS).

## CHAPTER FOUR

### RESULTS AND DISCUSSION

The results of the heavy metal analysis conducted on soil samples collected at a depth of 0–15 cm across the study area are presented in tables 4.1 to 4.4, which detail the mean concentration, standard error, min. and max. values, and associated health risk metrics. The concentrations of nine heavy metals; Iron (Fe), Zinc (Zn), Copper (Cu), Lead (Pb), Cadmium (Cd), Manganese (Mn), Nickel (Ni), Chromium (Cr), and Cobalt (Co) were quantified and evaluated. To assess the potential health implications of these contaminants, measured concentrations were compared against internationally recognized standards provided by the World Health Organization (WHO), 2011 and United States Environmental Protection Agency (USEPA), 2011 presented in table 4.1. The analysis included the Chronic Daily Intake (CDI), Hazard Quotient (HQ), and Hazard Index (HI) for both adults and children via the inhalation exposure pathway.

Table 4.1: Concentrations of Heavy Metals in Soil Samples and comparison with WHO and EPA standards

<b>Meta</b>	<b>Mean</b>	<b>Std</b>	<b>Min</b>	<b>Max</b>	<b>WHO (air,</b>	<b>USEPA</b>
<b>I</b>	<b>(mg/kg)</b>	<b>Error</b>	<b>(mg/kg)</b>	<b>(mg/kg)</b>	<b>µg/m<sup>3</sup>)</b>	<b>(mg/kg)</b>
Fe	53.41	2.01	45.96	65.70	-	-
Zn	25.52	1.01	21.74	31.38	-	23600
Cu	21.98	1.08	15.69	26.69	-	31600
Pb	2.51	0.11	1.91	3.04	-	200
Cd	0.73	0.08	0.38	1.14	0.005	70
Mn	6.37	0.14	5.64	7.18	-	1800
Ni	8.44	0.12	7.73	8.97	-	1500
Cr	5.40	0.08	5.07	5.88	-	230
Co	2.40	0.05	2.12	2.63	-	1000

Table 4.2: Chronic Daily Intake (CDI) via Inhalation for Adults and Children

<b>Metal</b>	<b>Mean Soil Conc. (mg/kg)</b>	<b>CDI Adults (mg/kg·day)</b>	<b>CDI Children (mg/kg·day)</b>
Fe	53.41	$3.83 \times 10^{-9}$	$2.16 \times 10^{-8}$
Zn	25.52	$1.83 \times 10^{-9}$	$1.03 \times 10^{-8}$
Cu	21.98	$1.58 \times 10^{-9}$	$8.96 \times 10^{-9}$
Pb	2.51	$1.80 \times 10^{-10}$	$1.01 \times 10^{-9}$
Cd	0.73	$5.22 \times 10^{-11}$	$2.96 \times 10^{-10}$
Mn	6.37	$4.57 \times 10^{-10}$	$2.59 \times 10^{-9}$
Ni	8.44	$6.05 \times 10^{-10}$	$3.43 \times 10^{-9}$
Cr	5.40	$3.88 \times 10^{-10}$	$2.20 \times 10^{-9}$
Co	2.40	$1.72 \times 10^{-10}$	$9.83 \times 10^{-10}$

Table 4.3: Hazard Quotient (HQ) via Inhalation

<b>Metal</b>	<b>RfC (mg/m<sup>3</sup>)</b>	<b>HQ Adults</b>	<b>HQ Children</b>
Cd	0.00065	0.000280	0.001586
Mn	0.000032	0.000032	0.000181
Cr	0.000035	0.000127	0.000225
Co	0.000006	0.000281	0.000499

Table 4.4: Hazard Index (HI)

<b>Metal Group</b>	<b>HQ Adults</b>	<b>HQ Children</b>
Cd, Mn, Cr, Co	0.000720	0.002491
Fe, Zn, Cu, Pb, Ni	-	-
<b>HI Total</b>	0.000720	0.002491

## DISCUSSION

The measured concentrations of metals in the studied soils exhibited moderate variability. Iron (Fe) concentrations ranged from 45.96 to 65.70 mg/kg with a standard error of 2.01 mg/kg, while cadmium (Cd), despite its lower mean concentration (0.73 mg/kg), displayed a wider relative range from 0.38 to 1.14 mg/kg with a standard error of 0.08 mg/kg. Zinc (Zn) and copper (Cu) similarly showed variability, with minimum values of 21.74 mg/kg and 15.69 mg/kg, respectively, highlighting localized differences in soil contamination (Haghighizadeh *et al.*, 2024).

### 4.1.2. Non-carcinogenic Risk Assessment

Human health risk assessment evaluates the potential adverse health effects arising from exposure to toxic metals in contaminated environments (Mohammadi *et al.*, 2019). In this study, the non-carcinogenic risks associated with exposure to heavy metals (Fe, Zn, Cu, Pb, Cd, Mn, Ni, Cr, and Co) through inhalation of contaminated soils were evaluated. The chronic daily intake (CDI), Hazard quotient (HQ) and Hazard index values for each metal are presented in Tables 4.2., 4.3. and 4.4.

The CDI values for adults ranged from  $1.80 \times 10^{-10}$  mg/kg·day for Pb to  $3.83 \times 10^{-9}$  mg/kg·day for Fe, whereas for children, the values ranged from  $1.01 \times 10^{-9}$  mg/kg·day for Pb to  $2.16 \times 10^{-8}$  mg/kg·day for Fe. These results reflect the relative concentrations of metals in soil and their potential contributions to human exposure through inhalation. Among the metals with available inhalation reference concentrations (RfC), cadmium (Cd) recorded the highest HQ values for both adults (0.000280) and children (0.001586), followed closely by cobalt (Co) and chromium (Cr). Manganese (Mn) recorded the lowest HQ values (0.000032 for adults and 0.000181 for

children), indicating relatively lower non-carcinogenic potential through inhalation (Cui *et al.*, 2023).

HQ values derived from the ratio of CDI to the inhalation reference concentration (RfC) provide a measure of potential non-carcinogenic health effects. For metals with RfC, the HQ values were well below the threshold of 1, suggesting that individual metals are unlikely to pose significant health risks through inhalation exposure. The cumulative hazard index (HI), representing combined exposure effects, was 0.000720 for adults and 0.002491 for children (Table 4.4), both significantly below the threshold ( $HI < 1$ ), indicating negligible non-carcinogenic risk from the metals with available inhalation reference values. Children exhibited slightly higher CDI, HQ, and HI values than adults, reflecting their greater vulnerability due to lower body weight and higher exposure relative to body mass (Rangasamy and Muniyandi, 2025).

The non-carcinogenic risk via inhalation of metals in the studied soils follows the decreasing order:  $Cd > Co > Cr > Pb > Fe > Zn > Cu > Ni > Mn$ , with all HI values below 1. This indicates that the exposed population, including children, is unlikely to experience adverse non-carcinogenic health effects from inhalation of the studied metals in the soil. The study highlights the importance of considering both quantitative and qualitative assessments, particularly when inhalation reference concentrations are unavailable for certain metals, to ensure a comprehensive evaluation of potential human health risks (Ahmad *et al.*, 2021).

## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATION

#### 5.0. Conclusion

The study revealed moderate variability in the concentrations of heavy metals in the analyzed soils, with Fe showing the highest concentrations and Cd displaying the widest relative range. Non-carcinogenic risk assessment via inhalation indicated that all individual metals, as well as the cumulative hazard index (HI), remained well below the threshold of concern ( $HI < 1$ ) for both adults and children. Cadmium posed the highest potential risk among the studied metals, followed by cobalt and chromium, while manganese exhibited the lowest risk. The findings suggest that exposure to these metals through soil inhalation is unlikely to result in adverse non-carcinogenic health effects, although children are marginally more susceptible due to higher relative exposure.

#### 5.1. Recommendations

Despite the low risk indicated, it is advisable to implement periodic monitoring of heavy metal concentrations in soils, particularly cadmium, cobalt, and chromium, to detect any future increases. Measures to minimize human exposure, such as promoting safe soil handling practices in residential areas are recommended.

## REFERENCES

- Adegbuyi, O. and Ogunyele, A. C. and Akinyemi, O. M, 2018. "Petrology and Geochemistry of Basement Gneissic Rocks around Oka-Akoko, Southwestern Nigeria. *Malaysian Journal of Geosciences (MJG)*, Zibeline International Publishing, **2**(2): 11-16.
- Adimalla, N. (2020). Heavy metals pollution assessment and its associated human health risk evaluation of urban soils from Indian cities: A review. *Environmental Geochemistry and Health*, **42**: 173–190.
- Aendo, P., Netvichian, R., Thiendedsakul, P., Khaodhiar, S. and Tulayakul, P. (2022). Carcinogenic risk of Pb, Cd, Ni, and Cr and critical ecological risk of Cd and Cu in soil and groundwater around the municipal solid waste open dump in central Thailand. *Journal of Environmental and Public Health*, 2022, 3062215.
- Ahmad, W., Alharthy, R. D. and Zubair, M. (2021). Toxic and heavy metals contamination assessment in soil and water to evaluate human health risk. *Scientific Reports*, **11**, 17006.
- Ahmed, J., Wong, L.P., Chua, Y.P., Channa, N., Memon, U.-u.-R., Garn, J.V., Yasmin, A. and VanDerslice, J.A. (2021). Heavy metals drinking water contamination and health risk assessment among primary school children of Pakistan. *Journal of Environmental Science and Health Part A* **56**: 667–679.
- Ahmed, M. F., Mokhtar, M. B., Alam, L., Mohamed, C. A. and Ta, G. C. (2020). Investigating the status of cadmium, chromium and lead in the drinking water supply chain to ensure drinking water quality in Malaysia. *Water*, **12**, 2653.
- Ajibade, A. C. and Wright, J. B. (1988). Structural relationships in the schist belts of northwestern Nigeria. In P. O. Oluyide, et al. (Eds.), *Precambrian geology of Nigeria* (pp. 103–109). Geological Survey of Nigeria.
- Ajibade, A. C., Woakes, M. and Rahaman, M. A. (1987). Proterozoic crustal development in the Pan-African regime of Nigeria. In A. Kröner (Ed.), *Proterozoic lithospheric evolution*.
- Ali, H., Khan, E. and Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry* **2019**: 1–14.
- Alsafran, M., Usman, K., Al Jabri, H. and Rizwan, M. (2021). Ecological and health risks assessment of potentially toxic metals and metalloids contaminants: A case study of agricultural soils in Qatar. *Toxics*, **9**: 35.

- Amin, S., Muhammad, S. and Fatima, H. (2021). Evaluation and risks assessment of potentially toxic elements in water and sediment of the Dor River and its tributaries, Northern Pakistan. *Environmental Technology & Innovation*, **21**: 101333.
- An, Y. J. and Kampbell, D. H. (2003). Total, dissolved, and bioavailable metals at Lake Texoma marinas. *Environmental Pollution*, **122**(2): 253–259.
- Bai, J. and Zhao, X. (2020). Ecological and human health risks of heavy metals in shooting range soils: A meta assessment from China. *Toxics*, **8**: 32.
- Baltas, H., Sirin, M., Gökbayrak, E. and Ozcelik, A. E. (2020). A case study on pollution and a human health risk assessment of heavy metals in agricultural soils around Sinop province, Turkey. *Chemosphere*, *241*, 125015.
- Bernardo, B., Candeias, C. and Rocha, F. (2022). Soil risk assessment in the surrounding area of Hulene-B waste dump, Maputo (Mozambique). *Geosciences*, **12**: 290.
- Bhatti, S. S., Kumar, V. and Nagpal, A. K. (2020). Potential carcinogenic and non-carcinogenic health hazards of metal(loid)s in food grains. *Environmental Science and Pollution Research*, **27**: 17032–17042.
- Chen, H., Zhan, C., Liu, S., Zhang, J., Liu, H., Liu, Z., Liu, T., Liu, X. and Xiao, W. (2022). Pollution characteristics and human health risk assessment of heavy metals in street dust from a typical industrial zone in Wuhan City, Central China. *International Journal of Environmental Research and Public Health*, **19**: 10970.
- Chen, H.L., Hsu, C.Y., Hung, D.Z. and Hu, M.L. (2006). Lipid peroxidation and antioxidant status in workers exposed to PCDD/Fs of metal recovery plants. *Science of the Total Environment* **372**: 12–19.
- Chen, R., Han, L., Liu, Z., Zhao, Y., Li, R., Xia, L. and Fan, Y. (2022). Assessment of soil-heavy metal pollution and the health risks in a mining area from southern Shaanxi Province, China. *Toxics*, **10**: 385.
- Chen, X., Huang, S., Xie, X., Zhu, M., Li, J., Wang, X. and Pu, L. (2020). Enrichment, source apportionment and health risk assessment of soil potentially harmful elements associated with different land use in coastal tidelands reclamation area, Eastern China. *International Journal of Environmental Research and Public Health*, **17**: 2822.
- Chorol, L. and Gupta, S. K. (2023). Evaluation of groundwater heavy metal pollution index through analytical hierarchy process and its health risk assessment via Monte Carlo simulation. *Process Safety and Environmental Protection*, *170*, 855–864.
- Chu, Z., Lin, C., Yang, K., Cheng, H., Gu, X., Wang, B., Wu, L. and Ma, J. (2022). Lability, bioaccessibility, and ecological and health risks of anthropogenic toxic heavy metals in

- the arid calcareous soil around a nonferrous metal smelting area. *Chemosphere*, **307**: 136200.
- Cirovic, A. and Satarug, S. (2024). Toxicity tolerance in the carcinogenesis of environmental cadmium. *International Journal of Molecular Sciences*, *25*, 1851.
- Coleman, N., Castrejon, A., Blaine, C. and Chemmachel, T. (2017). *The Toxicology of Essential and Nonessential Metals*, 11. Lulu.com.
- Cui, W., Mei, Y., Liu, S. and Zhang, X. (2023). Health risk assessment of heavy metal pollution and its sources in agricultural soils near Hongfeng Lake in the mining area of Guizhou Province, China. *Frontiers in public health*, **11**, 1276925.
- Cullinan, P., Munoz, X., Suojalehto, H., Agius, R., Jindal, S., Sigsgaard, T., Blomberg, A., Charpin, D., Annesi-Maesano, I., Gulati, M. and Kim, Y. (2017). Occupational lung diseases: from old and novel exposures to effective preventive strategies. *Lancet Respiratory Medicine* **5**(5): 445–455.
- Doležalová Weissmannová, H., Mihočová, S., Chovanec, P. and Pavlovský, J. (2019). Potential ecological risk and human health risk assessment of heavy metal pollution in industrial affected soils by coal mining and metallurgy in Ostrava, Czech Republic. *International Journal of Environmental Research and Public Health*, **16**: 4495.
- Dragović, S., Čujić, M., Slavković-Beškoski, L., Gajić, B., Bajat, B., Kilibarda, M. and Onjia, A. (2013). Trace element distribution in surface soils from a coal burning power production area: A case study from the largest power plant site in Serbia. *Catena*, **104**: 288–296.
- El-Alfy, M. A., Darwish, D. H. and El-Amier, Y. A. (2021). Land use land cover of the Burullus Lake shoreline (Egypt) and health risk assessment of metal-contaminated sediments. *Human and Ecological Risk Assessment: An International Journal*, **27**: 898–920.
- Elless, M. P., Bray, C. A. and Blaylock, M. J. (2007). Chemical behavior of residential lead in urban yards in the United States. *Environmental Pollution*, **148**(1): 291–300.
- Elsayed, Y., Dalibalta, S., Gomes, I., Fernandes, N. and Alqtaishat, F. (2016). Chemical composition and potential health risks of raw Arabian incense (Bakhour). *Journal of Saudi Chemical Society* **20**(4): 465–473.
- Ephraim, B. E., Ekwueme, B. N., Moazzen, M. and Modjarrad, M. (2008). PT conditions of Pan-African orogeny in southeastern Nigeria. *Central European Geology*, **51**(4): 359–378.

- Fan, T., Pan, J., Wang, X., Wang, S. and Lu, A. (2022). Ecological risk assessment and source apportionment of heavy metals in the soil of an opencast mine in Xinjiang. *International Journal of Environmental Research and Public Health*, **19**: 15522.
- Feary, J. and Cullinan, P. (2019). *Reference Module in Biomedical Sciences* [Internet]. Elsevier, Amsterdam, The Netherlands.
- Font, O., Moreno, T., Querol, X., Martins, V., Sanchez Rodas, D. and de Miguel, E. (2019). Origin and speciation of major and trace PM elements in the Barcelona subway system. *Transportation Research Part D: Transport and Environment* **72**: 17–35.
- Gandhi, D., Rudrashetti, A. P. and Rajasekaran, S. (2022). The impact of environmental and occupational exposures of manganese on pulmonary, hepatic, and renal functions. *Journal of Applied Toxicology*, **42**, 103–129.
- Giani, F., Mastro, R., Trovato, M. A., Malandrino, P., Russo, M., Pellegriti, G., Vigneri, P. and Vigneri, R. (2021). Heavy metals in the environment and thyroid cancer. *Cancers*, **13**, 4052.
- Gorka-Kostrubiec, B. (2015). The magnetic properties of indoor dust fractions as markers of air pollution inside buildings. *Building and Environment Journal* **90**: 186–195.
- Goumenou, M. and Tsatsakis, A. (2019). Proposing new approaches for the risk characterisation of single chemicals and chemical mixtures: The source related Hazard Quotient (HQS) and Hazard Index (HIS) and the adversity specific Hazard Index (HIA). *Toxicology Reports*, **6**: 632–636.
- Gradinaru, A.C., Solcan, G., Spataru, M.C., Hritcu, L.D., Burtan, L.C. and Spataru, C. (2019). The ecotoxicology of heavy metals from various anthropogenic sources and pathways for their bioremediation. *Revista de Chimie* **70**(7): 2556–2560.
- Gui, H., Yang, Q., Lu, X., Wang, H., Gu, Q. and Martín, J. D. (2023). Spatial distribution, contamination characteristics and ecological-health risk assessment of toxic heavy metals in soils near a smelting area. *Environmental Research*, **222**: 115328.
- Guney, M., Zagury, G. J., Dogan, N. and Onay, T. T. (2010). Exposure assessment and risk characterization from trace elements following soil ingestion by children exposed to playgrounds, parks and picnic areas. *Journal of Hazardous Materials*, **182**(1–3): 656–664.
- Gupta, S. and Gupta, S. K. (2023). Application of Monte Carlo simulation for carcinogenic and non-carcinogenic risks assessment through multi-exposure pathways of heavy metals of river water and sediment, India. *Environmental Geochemistry and Health*, **45**: 3465–3486.

- Haghighizadeh, A., Rajabi, O., Nezarat, A., Hajyani, Z., Haghmohammadi, M., Hedayatikhah, S., Delnabi Asl, S. and Aghababai Beni, A. (2024). Comprehensive analysis of heavy metal soil contamination in mining environments: Impacts, monitoring techniques, and remediation strategies. *Arabian Journal of Chemistry*, **17**(6), 105777.
- Hakanson, L. (1980). An ecological risk index for aquatic pollution control. A sedimentological approach. *Water Research*, **14**(8): 975-1001.
- Heidari, M., Darijani, T. and Alipour, V. (2021). Heavy metal pollution of road dust in a city and its highly polluted suburb; quantitative source apportionment and source-specific ecological and health risk assessment. *Chemosphere*, **273**: 129656.
- Hu, X., Zhang, Y., Luo, J., Wang, T., Lian, H. and Ding, Z. (2011). Bioaccessibility and health risk of arsenic, mercury and other metals in urban street dusts from a mega-city, Nanjing, China. *Environmental Pollution*, **159**(5): 1215–1221.
- Huang, S., Shao, G., Wang, L., Wang, L. and Tang, L. (2018). Distribution and health risk assessment of trace metals in soils in the Golden Triangle of Southern Fujian Province, China. *International Journal of Environmental Research and Public Health*, **16**: 97.
- Hwang, Y.H., Lin, Y.S., Lin, C.Y. and Wang, I.J. (2014). Incense burning at home and the blood lead level of preschoolers in Taiwan. *Environmental Science and Pollution Research* **21**: 13480–13487.
- IARC. (2019). *Agents classified by the IARC monographs, Vol. 1–123*.
- Isinkaralar, K., Isinkaralar, O. and Bayraktar, E.P. (2024). Ecological and health risk assessment in road dust samples from various land use of Düzce City Center: towards the sustainable urban development. *Water Air and Soil Pollution* **235**(2024): 84.
- Itam, Y.B, Ogar, V.O, Ekpenyong, E.E. and Ebong, E.E. (2024). Assessment of heavy metal contamination and risk associated with quarrying activities in Marksino Concession area, Akamkpa. *International Journal of Environment and Pollution Research*, **12**(2): 12-39.
- Jiang, H. H., Cai, L. M., Hu, G. C., Wen, H. H., Luo, J., Xu, H. Q. and Chen, L. G. (2021). An integrated exploration on health risk assessment quantification of potentially hazardous elements in soils from the perspective of sources. *Ecotoxicology and Environmental Safety*, **208**: 111489.
- Jiménez-Oyola, S., Chavez, E., García-Martínez, M. J., Ortega, M. F., Bolonio, D., Guzmán-Martínez, F., García-Garizabal, I. and Romero, P. (2021). Probabilistic multi-pathway human health risk assessment due to heavy metal(loid)s in a traditional gold mining area in Ecuador. *Ecotoxicology and Environmental Safety*, **224**: 112629.

- Kan, X., Dong, Y., Feng, L., Zhou, M. and Hou, H. (2021). Contamination and health risk assessment of heavy metals in China's lead-zinc mine tailings: A meta-analysis. *Chemosphere*, **267**: 128909.
- Karimi, A., Naghizadeh, A., Biglari, H., Peirovi, R., Ghasemi, A. and Zarei, A. (2020). Assessment of human health risks and pollution index for heavy metals in farmlands irrigated by effluents of stabilization ponds. *Environmental Science and Pollution Research*, **27**: 10317–10327.
- Kesler, S.E., Simon, A.C. and Simon, A.F. (2015). *Mineral resources, Economics and the Environment*, 26. Cambridge University Press.
- Khatoun, N., Ali, S., Hussain, A., Huang, J., Yu, Z. and Liu, H. (2025). Evaluating the Carcinogenic and Non-Carcinogenic Health Risks of Heavy Metals Contamination in Drinking Water, Vegetables, and Soil from Gilgit-Baltistan, Pakistan. *Toxics* **13**(1): 5.
- Khoshakhlagh, A.H., Ghobakhloo, S., Peijnenburg, W.J., Gruszecka-Kosowska, A. and Cicchella, D. (2024). To breathe or not to breathe: inhalational exposure to heavy metals and related health risk. *Science of the Total Environment* **27**: 172556.
- Koch, W., Czop, M., Iłowiecka, K., Nawrocka, A. and Wiącek, D. (2022). Dietary intake of toxic heavy metals with major groups of food products-results of analytical determinations. *Nutrients*, **14**, 1626.
- Kou, J., Gan, Y., Lei, S., Meng, W., Feng, C. and Xiao, H. (2022). Soil health and ecological risk assessment in the typical coal mines on the Mongolian Plateau. *Ecological Indicators*, **142**: 109189.
- Laidlaw, M. A. S. and Filippelli, G. M. (2008). Resuspension of urban soils as a persistent source of lead poisoning in children: A review and new directions. *Applied Geochemistry*, **23**(8): 2021–2039.
- Liu, H.H., Lin, M.H., Liu, P.C., Chan, C.I. and Chen, H.L. (2009). Health risk assessment by measuring plasma malondialdehyde (MDA), urinary 8-hydroxydeoxyguanosine (8-OH-dG) and DNA strand breakage following metal exposure in foundry workers. *Journal of Hazardous Materials* **170**(2–3): 699–704.
- Liu, L., Chen, J., Liu, C., Luo, Y., Chen, J., Fu, Y., Xu, Y., Wu, H., Li, X. and Wang, H. (2022). Relationships between biological heavy metals and breast cancer: A systematic review and meta-analysis. *Frontiers in Nutrition*, **9**, 838762.

- Liu, Z., Du, Q., Guan, Q., Luo, H., Shan, Y. and Shao, W. (2023). A Monte Carlo simulation-based health risk assessment of heavy metals in soils of an oasis agricultural region in Northwest China. *Science of the Total Environment*, **857**: 159543.
- Luo, W., Wang, T., Lu, Y., Giesy, J. P., Shi, Y., Zheng, Y., Xing, Y. and Wu, G. (2007). Landscape ecology of the Guanting Reservoir, Beijing, China: Multivariate and geostatistical analyses of metals in soils. *Environmental Pollution*, **146**(2): 567–576.
- Luo, X. S., Ding, J., Xu, B., Wang, Y. J., Li, H. B. and Yu, S. (2012). Incorporating bioaccessibility into human health risk assessments of heavy metals in urban park soils. *Science of The Total Environment*, **424**: 88–96.
- Luo, X., Yu, S. and Li, X. (2011). Distribution, availability, and sources of trace metals in different particle size fractions of urban soils in Hong Kong: Implications for assessing the risk to human health. *Environmental Pollution*, **159**(5): 1317–1326.
- Lv, J., Xia, Q., Yan, T., Zhang, M., Wang, Z. And Zhu, L. (2019). Identifying the sources, spatial distributions, and pollution status of heavy metals in soils from the southern coast of Laizhou Bay, eastern China. *Human and Ecological Risk Assessment: An International Journal*, **25**: 1953–1967.
- Maeaba, W., Prasad, S. and Chandra, S. (2019). First assessment of metals contamination in road dust and roadside soil of Suva City, Fiji. *Archives of environmental contamination and toxicology*, **77**: 249-262.
- Marcias, G., Fostinelli, J., Sanna, A.M., Uras, M., Catalani, S., Pili, S., Fabbri, D., Pilia, I., Meloni, F., Lecca, L.I. and Madeo, E. (2019). Occupational exposure to fine particles and ultrafine particles in a steelmaking foundry. *Journal of Metals* **9**(2): 163.
- McCurry, P. (1971). Pan-African orogeny in northern Nigeria. *GSA Bulletin*, **82**(11): 3251–3262.
- Meers, E., Du Laing, G., Unamuno, V., Ruttens, A., Vangronsveld, J., Tack, F. M. G. and Verloo, M. G. (2007). Comparison of cadmium extractability from soils by commonly used single extraction protocols. *Geoderma*, **141**(3–4): 247–259.
- Mohammadi, A. A., Zarei, A., Esmailzadeh, M., Taghavi, M., Yousefi, M., Yousefi, Z., Sedighi, F. and Javan, S. (2020). Assessment of heavy metal pollution and human health risks assessment in soils around an industrial zone in Neyshabur, Iran. *Biological Trace Element Research*, **195**, 343–352.
- Mohammadi, A. A., Zarei, A., Majidi, S., Ghaderpoury, A., Hashempour, Y., Saghi, M. H., Alinejad, A. and Yousefi, M. (2019). Carcinogenic and non-carcinogenic health risk

- assessment of heavy metals in drinking water of Khorramabad, Iran. *MethodsX*, **6**, 1642-1651.
- Mohammed, A. S., Kapri, A. and Goel, R. (2011). Heavy metal pollution: Source, impact, and remedies. In Khan, M. S., Zaidi, A., Goel, R. and Musarrat, J. (Eds.), *Bio-management of metal contaminated soils. Environmental Pollution*, **20**: 1–28. Springer, Dordrecht, The Netherlands.
- Morton-Bermea, O., Hernández-Álvarez, E., González-Hernández, G., Romero, F., Lozano, R. and Beramendi-Orosco, L. E. (2009). Assessment of heavy metal pollution in urban topsoils from the metropolitan area of Mexico City. *Journal of Geochemical Exploration*, **101**(3): 218–224.
- Mousavian, N.A., Mansouri, N. and Nezhadkurki, F. (2017). Estimation of heavy metal exposure in workplace and health risk exposure assessment in steel industries in Iran. *Measurement* **102**: 286–290.
- Muller, G.M. (1969). Index of geoaccumulation in sediments of the Rhine River. *Geojournal*, **2**: 108-118.
- Nikkila, R., Tolonen, S., Salo, T., Carpen, T., Pukkala, E. and Makitie, A. (2023). Occupational etiology of oropharyngeal cancer: a literature review. *International Journal of Environmental Research and Public Health* **20**(21): 7020.
- Nweke, N. D., Ugwuonah, E. N. And Onuba, L. N. (2024). The occurrences, characteristics, and implications of chaotic rocks (accretionary rocks) within the Trans-Saharan orogenic belt in Nigeria. *Discover Geoscience*, **2**: 95.
- Obasi, R. A. and Oluwatoyin, O. Akinola. (2020). The Migmatite and Gneisses in the Basement Complex of Southwestern Nigeria: a re-appraisal of their structural, mineralogical, and geochemical diversity. *IJRDO-Journal of Applied Science*, **6**(8): 01-17.
- Obiri-Nyarko, F., Duah, A. A., Karikari, A. Y., Agyekum, W. A., Manu, E. and Tagoe, R. (2021). Assessment of heavy metal contamination in soils at the Kpone landfill site, Ghana: Implication for ecological and health risk assessment. *Chemosphere*, **282**: 131007.
- Ogarekpe, N., Nnaji, C., Oyebode, O., Ekpenyong, M., Ofem, O., Tenebe, I. and Asitok, A. (2023). Groundwater quality index and potential human health risk assessment of heavy metals in water: A case study of Calabar metropolis, Nigeria. *Environmental Nanotechnology, Monitoring and Management*, **19**, 100780.

- Okorie, A., Entwistle, J. and Dean, J. R. (2011). The application of in vitro gastrointestinal extraction to assess oral bioaccessibility of potentially toxic elements from an urban recreational site. *Applied Geochemistry*, **26**(5): 789–796.
- Oves, M., Khan, M. S., Zaidi, A. and Ahmad, E. (2012). Soil contamination, nutritive value, and human health risk assessment of heavy metals: An overview. In Zaidi, A., Wani, P. A. and Khan, M. S. (Eds.), *Toxicity of heavy metals to legumes and bioremediation*, pp. 1–27. Springer, Vienna, Austria.
- Oyedoh, E.A., Okwah, G.A. and Oshomogho, F.O (2023). Physicochemical Characteristics of Clay Mineral from Ikpeshi in Akoko-Edo Local Government Area, Edo State, Nigeria. *Journal of Applied Sciences and Environmental Management*, **27**(6): 1119-1125.
- Oyewole, A.M. and Ofuyah, W.N. (2017). The Geology of Eshiwawa in Igarra Area, Southwestern Nigeria. *International Journal of Research*, **4**(6): 1265-1274.
- Pecina, V., Brtnický, M., Baltazár, T., Jurička, D., Kynický, J. and Vašinová Galiová, M. (2021). Human health and ecological risk assessment of trace elements in urban soils of 101 cities in China: A meta-analysis. *Chemosphere*, **267**: 129215.
- Peijnenburg, W. J. G. M. and Jager, T. (2003). Monitoring approaches to assess bioaccessibility and bioavailability of metals: Matrix issues. *Ecotoxicology and Environmental Safety*, **56**(1): 63–77.
- Peijnenburg, W. J. G. M., Zablotskaja, M. and Vijver, M. G. (2007). Monitoring metals in terrestrial environments within a bioavailability framework and a focus on soil extraction. *Ecotoxicology and Environmental Safety*, **67**(2): 163–179.
- Praveena, S. M., Yuswir, N. S. and Hashim, Z. (2015). Contamination assessment and potential human health risks of heavy metals in Klang urban soils: a preliminary study. *Environmental Earth Sciences*, **73**: 8155–8165.
- Qishlaqi, A., Moore, F. and Forghani, G. (2009). Characterization of metal pollution in soils under two landuse patterns in the Angouran region, NW Iran; a study based on multivariate data analysis. *Journal of Hazardous Materials*, **172**(1): 374–384.
- Rahaman, M.A. (1988) Recent Advances in the Study of the Basement Complex of Nigeria. In Precambrian Geology of Nigeria, Geological Survey of Nigeria, Kaduna South, 11-43.
- Raj, D., Kumar, A., Tripti and Maiti, S. K. (2022). Health risk assessment of children exposed to the soil containing potentially toxic elements: A case study from coal mining areas. *Metals*, **12**: 1795.

- Rangasamy, E. and Muniyandi, M. (2025). Assessment of heavy metal pollution and human health risk in the soil of selected tea plantations from southern Western Ghats, Tamil Nadu, India. *Toxicology reports*, **15**, 102081.
- Raymond, R. (1986). Out of the fiery furnace: The impact of metals on the history of mankind. *Penn State Press*, University Park, PA, USA.
- Rehman, K., Fatima, F., Waheed, I. and Akash, M.S.H. (2018). Prevalence of exposure of heavy metals and their impact on health consequences. *Journal of Cellular Biochemistry* **119**(1): 157–184.
- Rohlman, D.S., Nuwayhid, I., Ismail, A. and Saddik, B. (2012). Using epidemiology and neurotoxicology to reduce risks. *Neurotoxicology Research*.
- Sajjadi, S. A., Mohammadi, A., Khosravi, R. and Zarei, A. (2022). Distribution, exposure, and human health risk analysis of heavy metals in drinking groundwater of Ghayen County, Iran. *Geocarto International*, *37*, 13127–13144.
- Salami, A. S., Babafemi, E. M. and Akperi, O. G. (2024). Basement groundwater potentials evaluation using resistivity method: Ogugu and environs, Akoko-Edo, Southwestern Nigeria as a case study. *International Journal of Earth Sciences Knowledge and Applications*, **6**(1): 29–36.
- Saleem, M., Iqbal, J. and Shah, M. H. (2014). Non-carcinogenic and carcinogenic health risk assessment of selected metals in soil around a natural water reservoir, Pakistan. *Ecotoxicology and Environmental Safety*, **108**: 42–51.
- Samaila, B., Aisha, I., Shehu, A. and Bako, A. (2021). Evaluation of chronic daily intake, pollution index and incremental life cancer risk to adults due to exposures to heavy metals in surface and ground water. *International Journal of Scientific Research in Physical and Applied Sciences*, **9**: 72–80.
- Sanni, E.B., Samuel, O.O., Mohammed, M.M., Momoh, S.D. and Oyemi, O.G. (2023). Application of Geophysical Technique in Delineation of Marble Deposit in Ikpeshi, Edo, Nigeria. *African Journal of Environment and Natural Science Research*, **6**(3): 46-66.
- Sarim, M., Jan, T., Khattak, S. A., Mihoub, A., Jamal, A., Saeed, M. F., Soltani-Gerdefaramarzi, S., Tariq, S. R., Fernández, M. P. and Mancinelli, R. (2022). Assessment of the ecological and health risks of potentially toxic metals in agricultural soils from the Drosh-Shishi Valley, Pakistan. *Land*, **11**: 1663.

- Scott, N.B. and Pocock, N.S. (2021). The health impacts of hazardous chemical exposures among child labourers in low-and middle-income countries. *International Journal of Environmental Research and Public Health* **18**(10): 5496.
- Sharifi, F., Arab-Amiri, A.R., Kamkar-Rouhani, A. And Alipour-Asll, M. !(2019). Combining a robust PCA of logratio transformed data and geostatistical sequential Gaussian simulation approach for geochemical characterization of orogenic gold deposits: a case study from the Alut area, northwest of Iran. *Geochemistry: Exploration, Environment, Analysis*, **20**: 1.
- Taiwo, B. O. and Omotehinse, A. O. (2022). The economic potential of some metacarbonate rocks in Akoko-Edo, Edo State, Nigeria. *Applied Earth Science*, **131**(3): 167–178.
- Tamers, S.L., Streit, J., Pana-Cryan, R., Ray, T., Syron, L., Flynn, M.A., Castillo, D., Roth, G., Geraci, C., Guerin, R. and Schulte, P. (2020). Envisioning the future of work to safeguard the safety, health, and well-being of the workforce: a perspective from the CDC’s National Institute for Occupational Safety and Health. *American Journal of Industrial Medicine* **63**(12): 1065–1084.
- Tomlinson, D.L., Wilson, J.G., Harris, C.R. and Jeffrey, D.W. (1980). Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgoländer Meeresuntersuchungen*, **33**: 566-575.
- Udi, E. M., Imasuen, O. I., Avwenagha, E. O. And Odokuma-Alonge, O. (2023). Examination of the Pan–African orogeny: Implications on the architecture of basement rocks in Igarra, Southwestern Nigeria. *International Journal of Earth Sciences Knowledge and Applications*, **5**(1): 92–102.
- Udinmwun, E. (2017). Palaeostress configuration of Pan-African orogeny: Evidence from the Igarra schist belt, SW Nigeria. *Iranian Journal of Earth Sciences*, **9**(1): 85–93.
- ur Rehman, I., Ishaq, M., Ali, L., Khan, S., Ahmad, I., Din, I. U. and Ullah, H. (2018). Enrichment, spatial distribution of potential ecological and human health risk assessment via toxic metals in soil and surface water ingestion in the vicinity of Sewakht mines, District Chitral, Northern Pakistan. *Ecotoxicology and Environmental Safety*, **154**: 127–136.
- USEPA (U.S. Environmental Protection Agency) (2016). Regional Screening Levels (RSLs)-User’s Guide available
- USEPA. (2025). Regional screening levels (RSLs)—User’s guide. *United States Environmental Protection Agency*. Available online: <https://www.epa.gov/risk/regional-screening-levels-rsls-users-guide> (accessed on 02 July 2025).

- Ustaoglu, F. and Islam, M. S. (2020). Potential toxic elements in sediment of some rivers at Giresun, northeast Turkey: A preliminary assessment for ecotoxicological status and health risk. *Ecological Indicators*, **113**: 106237.
- Verma, N., Rachamalla, M., Kumar, P.S. and Dua, K. (2023). Assessment and impact of metal toxicity on wildlife and human health. In: *Metals in Water*: 93–110.
- Vidal, O., Rostom, F., François, C. and Giraud, G. (2017). Global trends in metal consumption and supply: The raw material–energy nexus. *Elements*, **13**: 319–324.
- Waalkes, M. P. and Misra, R. R. (2023). Cadmium carcinogenicity and genotoxicity. In *Toxicology of Metals, Volume I* (pp. 231–243). CRC Press.
- Wang, J., Gao, B., Yin, S., Xu, D., Liu, L. and Li, Y. (2019). Simultaneous health risk assessment of potentially toxic elements in soils and sediments of the Guishui River Basin, Beijing. *International Journal of Environmental Research and Public Health*, **16**: 4539.
- Wang, X. F., Deng, C. B. and Zhu, K. X. (2020). Risk assessments of heavy metals to children following non-dietary exposures and sugarcane consumption in a rural area in Southern China. *Exposure and Health*, **12**: 1–8.
- Wang, Z., Zhang, J. and Watanabe, I. (2022). Source apportionment and risk assessment of soil heavy metals due to railroad activity using a positive matrix factorization approach. *Sustainability*, **15**: 75.
- Wu, J., Lu, J., Li, L., Min, X. And Luo, Y. (2018a). Pollution, ecological-health risks, and sources of heavy metals in soil of the northeastern Qinghai-Tibet Plateau. *Chemosphere*, 234–242.
- Yakameran, E., Ari, A. and Aygün, A. (2021). Land application of municipal sewage sludge: Human health risk assessment of heavy metals. *Journal of Cleaner Production*, 319, 128568.
- Yan, L., Franco, A. M. and Elio, P. (2021). Health risk assessment via ingestion and inhalation of soil PTE of an urban area. *Chemosphere*, **281**: 130964.
- Yang, Q., Zhang, L., Wang, H. and Martín, J. D. (2022). Bioavailability and health risk of toxic heavy metals (As, Hg, Pb and Cd) in urban soils: A Monte Carlo simulation approach. *Environmental Research*, **214**: 113772.
- Zglobicki, W. and Telecka, M. (2021). Heavy metals in urban street dust: health risk assessment (Lublin City, E Poland). *Applied Sciences*, **11**(9): 4092.

- Zhang, R., Chen, T., Zhang, Y., Hou, Y. and Chang, Q. (2020). Health risk assessment of heavy metals in agricultural soils and identification of main influencing factors in a typical industrial park in Northwest China. *Chemosphere*, **252**: 126591.
- Zhang, Y., Wang, S., Gao, Z., Zhang, H., Zhu, Z., Jiang, B., Liu, J. and Dong, H. (2021). Contamination characteristics, source analysis and health risk assessment of heavy metals in the soil in Shi River Basin in China based on high density sampling. *Ecotoxicology and Environmental Safety*, **227**: 112926.
- Zhao, L., Islam, R., Wang, Y., Zhang, X. and Liu, L.-Z. (2022). Epigenetic regulation in chromium-, nickel- and cadmium-induced carcinogenesis. *Cancers*, *14*, 5768.
- Zhou, P., Zeng, D., Wang, X., Tai, L., Zhou, W., Zhuoma, Q. and Lin, F. (2022). Pollution levels and risk assessment of heavy metals in the soil of a landfill site: A case study in Lhasa, Tibet. *International Journal of Environmental Research and Public Health*, **19**: 10704.
- Zhou, Y., Jiang, D., Ding, D., Wu, Y., Wei, J., Kong, L., Long, T., Fan, T. and Deng, S. (2022). Ecological-health risks assessment and source apportionment of heavy metals in agricultural soils around a super-sized lead-zinc smelter with a long production history, in China. *Environmental Pollution*, **307**: 119487.
- Zhou, Y., Niu, L., Liu, K., Yin, S. and Liu, W. (2018). Arsenic in agricultural soils across China: Distribution pattern, accumulation trend, influencing factors, and risk assessment. *Science of the Total Environment*, **616–617**: 156–163