GEOCHEMICAL CHARACTERISATION OF SOIL AND ROAD DUST FROM AN INFORMAL SETTLEMENT AND THEIR POSSIBLE HEALTH IMPLICATIONS: A STUDY OF WINNIE MANDELA INFORMAL SETTLEMENT, GAUTENG, SOUTH AFRICA

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DECLARATION

I, Innocent Mugudamani, student number __________, do hereby declare that this research project submitted to the Central University of Technology, Free State, for the Master of Health Sciences in Environmental Health, is my own independent work; and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State; and has not been submitted before to any institution by myself or any other person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

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ABSTRACT

In Africa, different types of informal settlements are rising in quantities, capacities and population. The large population in urban informal settlements lead to a huge accumulation of wastes and the release of chemicals such as heavy metals to the surrounding environment. The aim of the study was to give an overview on the current heavy metal content in soil and road dust from the Winnie Mandela informal settlement in Gauteng, South Africa, and to evaluate its possible health risks. The current major and trace elements in soil and road dust samples were analysed by the wavelength dispersive X-ray fluorescence method, whereas the mineralogical compositions of soil and road dust were analysed by the X-ray diffraction method. The pollution status of soil and road dust were assessed by a geo-accumulation index, contamination factor, pollution load index and enrichment factor, while health risks were assessed by a health risk assessment model.

The findings of the study exhibited quartz as a dominated mineral in both soil and road dust. The concentrations of major elements in soil were descending as silicone dioxide, aluminium oxide, iron oxide, manganese oxide, potassium oxide, titanium dioxide, calcium oxide, magnesium oxide, phosphorus pent-oxide, sodium oxide, with iron oxide, phosphorus pent-oxide, silicone dioxide and titanium dioxide higher than their average shale values. In road dust, major elements were as silicon dioxide, aluminium oxide, iron oxide, calcium oxide, potassium oxide, sodium oxide, magnesium oxide, manganese oxide, titanium dioxide, phosphorus pent-oxide with silicon dioxide and phosphorus pent-oxide above their average shale values. Moreover, seventeen (17) trace elements (As, Ba, Co, Cr, Cu, Nb, Ni, Pb, Rb, Sc, Sr, Th, U, V, Y, Zn, Zr) were analysed in soil and road dust. Their mean concentrations in soil samples were descending as Cr > Ba > Zr > V > Zn > Ni > Cu > Rb > Sr > Co > Pb > As > Y > Sc > Nb > Th > U, with As, Co, Cr, Cu, Nb, Ni, Pb, Zn, Zr, V and Zr above their average shale values. In road dust, they were Cr > Ba > Zn > Zr > Sr > V > Rb > Cu > Ni > Pb > Co > Y > Nb > As > Sc > Th > U. Trace elements such as Ba, Cr, Cu, Pb, Zn and Zr surpassed their average shale values.

The assessment of pollution through the geo-accumulation index revealed that the quality of soil and road dust was moderately to heavily contaminated by Cr, whereas all other elements were categorised as uncontaminated to moderately contaminated. According to the contamination factor, Cr was classified as very high contamination in soil, whereas As, Co, Cu, Nb, Ni, Pb, Sc, V, Zn and Zr were categorised as moderate contamination. Elements such as Ba, Rb, Sr, Th, U and Y were regarded as low contamination. It further exhibited road dust to be very highly contaminated by Cr, moderately contaminated by Ba, Cu, Pb, Zn and Zr, and lowly contaminated by As, Co, Nb, Ni, Rb, Sc, Sr, Th, U, V and Y. Additionally, the pollution load index also affirmed that soil and road dust in this study were very highly polluted by heavy metals, which substantiates the findings that human activities can exacerbated the level of trace elements in urban settings. Moreover, the results of the enrichment factor in soil and road dust categorised Cr as significant enrichment, possibly from the influence of human activities. In soil and road dust, Co and Zn were elucidated as minimal enrichment, respectively, whereas all other trace elements in soil and road dust were of natural origin. The results of the pollution indices also revealed that trace elements in this study had natural and anthropogenic origins.

Furthermore, the results of the noncarcinogenic risk assessment in soil revealed a possibility of noncarcinogenic risk to children and adults. In road dust, a possibility of noncarcinogenic risks to children and adults were also found. Children were at higher risk of non-carcinogenic than adults in both soil and road dust. For carcinogenic risk in soil, the total carcinogenic risk values in children and adults were above the acceptable limit signifying a likelihood of carcinogenic risk to the local inhabitants. In road dust, the carcinogenic risk assessment also exhibited a chance of carcinogenic risk to children and adults. The study revealed that children are at higher carcinogenic risk than the adult population. Exposure to As, Ba, Co, Cr, Cu, Nb, Ni, Pb, Zn, V and Zr, which were above their average shale values, may lead to cancer, miscarriages, hearing and visual impairment, asthma, renal failure, high blood pressure, headaches and dizziness, or reproductive system problems and cardiovascular disorders among the local residents.

Therefore, this study concluded that activities in urban informal settlements contribute significantly to the rise of heavy metal in soil and road dust. Furthermore, the local residents may suffer non-carcinogenic and carcinogenic risks due to high concentrations of trace elements in soil and road dust. Thus, proper waste management, remediation, cleaning and regular monitoring of heavy metals are recommended for the safety of the population and sustainability of the settlement.

Key words: geochemical; informal settlement; health implications; soil; road dust; major and trace elements; X-ray fluorescence; X-ray diffraction; pollution indices; health risk assessment model

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DEDICATION

This study is dedicated to the Lord and Saviour, Jesus Christ, who furnished me with an opportunity, strength, good health, and wisdom to further my career. I will forever be grateful.

To Him be the glory.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

ADD	Average daily dose
ANOVA	Analysis of variance
ASV	Average shale value
CBD	Central business distribution
CF	Contamination factor
CR	Carcinogenic risk
EF	Enrichment factor
GDP	Gross domestic product
HI	Hazard index
HIV	Human immunodeficiency virus
HQ	Hazard quotient
Igeo	Geo-accumulation index
LADD	Lifetime average daily dose
LOI	Loss on ignition
NAAQS	National Ambient Air Quality Standards
PLI	Pollution load index
$PM_{2.5}$	Particles with an aerodynamic diameter of less than 2.5 μm
PM_{10}	Particles with an aerodynamic diameter of less than 10 μm
RDP	Reconstruction and development programme
RfD	Reference dose
SD	Standard deviation
SF	Slope factor
SIMRAC	Safety in Mines Research Advisory Committee
SPSS	Statistical Package for the Social Sciences
StatsSA	Statistic South Africa
TCR	Total carcinogenic risk
THI	Total hazard index
USEPA	United States Environmental Protection Agency
WD-XRF	Wavelength dispersive X-ray fluorescence
XRD	X-ray diffraction
XRF	X-ray fluorescence

LIST OF CHEMICAL SYMBOLS

Al	Aluminium
Al_2O_3	Aluminium oxide
Ag	Silver
As	Arsenic
Ba	Barium
Ca	Calcium
CaO	Calcium oxide
Cd	Cadmium
Ce	Cerium
Co	Cobalt
Cr	Chromium
Cu	Copper
Fe	Iron
Fe_2O_3	Iron oxide
Hg	Mercury
Ir	Iridium
K_2O	Potassium oxide
La	Lanthanum
Mg	Magnesium
MgO	Magnesium oxide
Mo	Molybdenum
Mn	Manganese
MnO	Manganese oxide
Na_2O	Sodium oxide
Nb	Niobium
Ni	Nickel
NO_2	Nitrogen dioxide
NOx	Nitric oxide and nitrogen dioxide
Os	Osmium
P	Potassium
Pb	Lead
Pd	Palladium
Pt	Platinum
P_2O_5	Phosphorus pent-oxide
Rb	Rubidium
Rh	Rhodium
Ru	Ruthenium
S	Sulphur
Sb	Antimony
Sc	Scandium
Se	Selenium
SiO_2	Silicon dioxide/Silica
SO_2	Sulphur dioxide
Sr	Strontium
Th	Thorium
Ti	Titanium
TiO_2	Titanium dioxide
Tl	Thallium
U	Uranium
V	Vanadium
Y	Yitrium
Zn	Zinc
Zr	Zirconium
ZrO_2	Zirconia dioxide

LIST OF MEASURING UNITS

°C	Degree Celsius
%	Percentage
kg	Kilogram
Ma	Mega annum
m/s	Metre per second
mg	Milligram
mg/kg	Milligram per kilogram
mg/kg/d	Milligram per kilogram per day
m^2	Square metre
m^3	Cubic metre
Ng	Nano gram
nm	Nanometre
ppb	Particle per billion
ppm	Particle per million
Λ	Wavelength
µm	Micrometre
±SD	Standard deviation

LIST OF ACADEMIC OUTPUTS FROM THIS DISSERTATION

Published work:

Mugudamani, I., Oke S.A., Gumede, T.P. (2022). Heavy metal pollution and public health: A review of heavy metal pollution, health implications, and potential used methods for pollution assessment. In: *Trace metals: Sources, applications and environmental implications*, edited by Thygesen O.M., pp. 63-87. Nova Science Publishers. (Analytical Chemistry and Microchemistry Series). ISBN: 978-1-68507-797-6

Mugudamani, I., Oke, S.A., Gumede, T.P. (2022). Influence of urban informal settlements on trace element accumulation in road dust and their possible health implications in Ekurhuleni Metropolitan Municipality, South Africa. *Toxics*, 10(5):253. https://doi.org/10.3390/toxics10050253

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Mugudamani, I., Oke, S.A., Gumede, T.P. Geochemical impact of urban informal settlement in developing countries on environmental sustainability: An overview **(To be submitted for journal publication)**.

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CHAPTER 1
INTRODUCTION

1.1 Background to the problem

One of the main challenges of the twenty-first century is urbanisation. The United Nations have projected that by 2050, 68% of the world population will be residing in urban environments (United Nations 2018; Parikh et al. 2020). Universally, informal settlements form a major part of urban landscape due to urbanisation and an upsurge in the population (Marutlulle 2017; Parikh et al. 2020). The urban landscape of most developing countries has experienced the manifestation of informal settlements for many years. As urban areas expand, the development of informal settlements also escalate (Msimang 2017). Africa is marked by different types of informal settlements (United Nations Centre for Human Settlements [Habitat] 2001:15), which is rising in quantity, capacity and population (Kombe and Kreibich 2007; Mwamhanga 2013). The majority of urban inhabitants (~55%) in sub-Saharan African now reside in overcrowded informal settlements (Weimann and Oni 2019).

The population of the informal settlement upsurges on a daily basis and contribute to the high generation of waste, thus making it a highly contaminated area. Furthermore, inhabitants are confronted with a myriad of environmental challenges such as fading flora, soil erosion, air, water and soil contamination (Msimang 2017). Environmental contamination triggered by heavy metals is a major problem for developing countries due to urbanisation and industrialisation (Newaz 2020; Yousuf et al. 2017). Generally, urban informal settlements increase the concentration of heavy metals through activities such as transport, household heating, combustion of coal and oil, industrial processes, burning of waste, unplanned construction, weathering of roads and maintenance of roads (Charlesworth et al. 2011). Wastes from, foodstuff, petroleum, and health care, personal care and cosmetic products also contribute to the addition of heavy metals in urban informal settlements (Singo 2013). Consequently, the concentration of heavy metal contamination exceed the background values in many urban environments (Men et al. 2018, Newaz 2020).

According to Gabarrón et al. (2017), the accumulation of metals and metalloids in soil is a universal challenge due to their persistent, nondegradable and toxicity nature. Any metallic element that is toxic is regarded as a heavy metal (Duruibe et al. 2007; Lenntech Water Treatment and Air Purification 2004). Moreover, it also relates to essential elements needed at little amounts in organisms (Adriano 2001). Harmful elements such as lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), arsenic (As) and vital elements such as copper (Cu), zinc (Zn), cobalt (Co), manganese (Mn) and nickel (Ni) are common heavy metal pollutants in urban environments (Sezgin et al. 2019). Generally, the environmental load of heavy metals has increased intensively as a result of industrialisation. Heavy metals are persistent in all environmental compartments as they do not decompose and as such it is impossible for anybody to evade contact (Singo 2013).

Even unpolluted soils in their natural state may have heavy metals (Vince et al. 2014) and their occurrence in soil mainly depends on the composition of parent materials and its geogenic processes (Gabarrón et al. 2017). Human activities, such as population increases (Gabarrón et al. 2017), vehicle emissions, industrial activities, disposal of municipal waste, coal power plants, mining and smelting processes (Sezgin et al. 2019), contribute to the accumulation of heavy metals in urban environments. Soil and road dust are potential pointers of an increase in toxic elements in urban environments. This is because they are not decomposable and can persist for a long time in the environment (Gabarrón et al. 2017). Oke and Vermeulen (2016) also found that heavy metals deposited into the environment may have negative effects on the environment and human health.

Urban spaces in predominantly informal settlements are typically overcrowded. In addition, traffic flow as well as the transport system pushes on a daily basis for its rapid urbanisation and business activities. It increases exhaust emissions, industrial emissions, petrochemical leaks, automobile parts and particulate emissions, which could directly to affecting the inhabitants, pedestrians and those who use such spaces (Newaz 2020). Furthermore, people in this communities could be exposed to potentially harmful elements by means of inhalation, ingestion and dermal contact. Human exposure to trace element contaminants in soil and road dust can cause medical implications that affect nervous, renal, cardiovascular and reproductive systems, as well as development delay in children, or cause carcinogenic effects (Christoforidis et al. 2009). Individuals with a weak immune system or compromised by age, and those who ingest significant amounts of dust unintentionally through a hand-to-mouth route, are more susceptible to be harmed by heavy metals (Ma and Singhirunnusorn 2012).

In South Africa, informal settlements are home-based to masses of households and Ekurhuleni is one of the metropolitan municipalities with roughly 26% of its inhabitants residing in informal settlements (Tissington 2011), such as the Winnie Mandela informal settlement. Previously, many studies were conducted on trace element contamination in soil and road dusts in developed nations or in megacities. However, in South Africa, little or no distinct studies have been carried out on soil and road dust contamination of heavy metals from poor informal settlements. To our knowledge, information on heavy metal contamination in soil and road dusts collected from urban informal settlements is deficient. This study sought to address the research gap that currently exists regarding the content of trace elements in soil and road dust, the level of pollution and source of pollutants in informal settlements as well as their possible health risks. The findings of this study can offer basic information for community settlement regulators and urban developers or municipalities on the level of heavy metal accumulated in soil and road dust in informal settlements and its possible health implications.

1.2 Problem statement

Almost half of the global population resides in urban environments, and their health conditions and living surroundings have become a serious concern (Weimann and Oni 2019). The urban landscape of most developing nations has experienced the proliferation of informal settlements for many years. As urban areas expand, the development of informal settlements also escalate (Msimang 2017). In Africa, the majority of sub-Saharan African urban inhabitants (~55%) now reside in informal settlements (Weimann and Oni 2019). Informal settlements are reflected as congested, high generators of waste and extremely contaminated areas (Msimang 2017). Land pollution by heavy metals is hazardous because they are persistent and nondegradable in the environment (Singo 2013). The biota, animal and human beings suffer the penalties of a long time impact of heavy metal pollution on the environment

(Oke and Vermeulen 2016). Heavy metals are persistent in all environmental compartments as they are nondegradable and as such it is impossible for anybody to evade contact (Singo 2013). Even unpolluted land in its natural state may have heavy metals, which are deposited into the soil through the process of rock weathering (Vince et al. 2014). Since many medical complications are associated with the condition of the urban settings (Filippelli et al. 2012), each citizen should be keen to know the geochemistry of the land they reside in. The majority of previous studies were conducted on the effects of urban soil and road dusts in developed nations or in megacities, with little focus on geochemistry and health risk assessment of soil and road dust in informal settlements. Lack of data currently makes it difficult to quantify the degree of trace element contamination and health risk associated with living in informal settlements. Therefore, there is a need to carry out a detailed geochemical assessment of soil and road dust from an informal settlement in South Africa, as well as evaluating its potential impact on the health of residents, and those using such places.

1.3 Research questions

The research sought to clarify and provide answers to various questions, and thereafter, utilise the information gathered to assess health risks resulting from the exposure of trace elements in soil and road dust. These questions include:

1. What are the major and trace element contaminants released into an urban informal settlement's soil and road dust?
2. What is the degree of trace element contamination in soil and road dust affected by an urban informal settlement's activities?
3. What are the main pollutant sources of trace elements in an urban informal settlement?
4. What is the possible health risk associated with trace element exposure in soil and road dust from an informal settlement?

1.4 Research hypotheses

The research hypotheses are:

1. Activities in an urban informal settlement does contribute to heavy metal pollution.

2. The concentration level of heavy metal in soil and road dust in an urban informal settlement is very high.

1.5 Aim and objectives

Given the problem statement described above, the study aimed to give an overview on the current heavy metal content in soil and road dust from Winnie Mandela informal settlement in Gauteng, South Africa, and evaluate its possible health risks. The following specific research objectives were considered:

1. To establish the major and trace element contaminants released into an urban informal settlement's soil and road dust.
2. To assess the degree of trace element pollution in soil and road dust affected by an urban informal settlement's activities.
3. To identify the main pollutant sources of trace elements in an urban informal settlement.
4. To assess the health risks associated with trace element exposure in an urban informal settlement and determine their possible health implications.

1.6 Significance of the study

Heavy metals are persistent in all environmental compartments as they are non-degradable and as such it is impossible for anyone to evade contact (Singo 2013). Even unpolluted land in their natural state may contain heavy metals, which are deposited into the soil through weathering of rocks (Vince et al. 2014). According to Newaz et al. (2020), in developing nations, environmental contamination by heavy metals is problematic due to the rapid urbanisation, industrialisation, food production practices, land use, and population increase.

Generally, urban environments have been intensively altered by anthropogenic activities, such as automobiles and industrial activities as they are characterised by high population concentrations. Heavy metals do not decompose in dust or a soil environment. They persist in soil for a long period or be entrained in the air, presenting a potential medical problem to human beings (Ghanavati 2018). Health problems such as the nervous, renal, cardiovascular, reproductive systems, as well as development delay in children or carcinogenic effects, may occur as a result of heavy metal exposure (Christoforidis et al. 2009).

Consumption of considerable quantities of resources by the large population in urban settings, particularly informal settlements, leads to production of large volume of waste daily (Newaz et al. 2020). As a result, discharge of both inorganic and organic contaminants are regularly massively accelerated, making the urban environment prone to environmental degradation and pollution (Thornton 1993). The assessment of pollution levels and risks associated with heavy metals on inhabitants and environment is therefore of great importance (Newaz et al. 2020).

This study aimed to contribute to the body of knowledge and report on the knowledge gaps in the literature pertaining to the geochemical composition of urban informal settlement soil and road dust and their possible health risks. It will help to create awareness of the present contamination of urban informal settlement soils and road dust. Moreover, the study hope to raise awareness among the nation and local inhabitants about the contribution of informal settlements to heavy metal pollution in soil and road dust and their possible health risks. The study will also be of great benefit for fellow scholars, as it will serve as a basis for further research on geochemistry and health risk assessment of urban informal settlement's soil and road dust. Furthermore, this study will assist the researcher to integrate the theoretical knowledge into practical application in a geochemistry and health aspect.

1.7 Scope of the study

The study focused on the major and trace elements of an urban informal settlement's soil and road dust. Sampling and analysis of soil and road dust was conducted in order to establish the type of trace element contaminants released into an urban informal settlement. The contamination level and source of pollutants were also assessed. Furthermore, the risks associated with trace elements exposure were assessed and possible health implications of identified trace elements were addressed.

1.8 Limitations of the study

The study was limited to the assessment of the concentration of major and trace elements, degree and sources of trace elements, and its associated health risks in an urban informal settlement's soil and road dust, thus, the study did not consider the following:

- An investigation of indoor dust.
- The effects of seasonal variations on trace element contamination in soil and road dust.
- The morphology and particle size distribution in soil and road dust.

1.9 Structure of the dissertation

This dissertation is made up of six chapters outlined as follows:

Chapter 1: Introduction

Chapter 1 covers the background to the problem, problem statement, research questions, research hypotheses, aims and objectives, significance, scope and limitations of the study.

Chapter 2: Literature review

Chapter 2 gives an overview of the geochemical impact of urban informal settlement in developing countries on environmental sustainability.

Chapter 3: Background of the study area

In chapter 3, a detailed description of the study area is provided.

Chapter 4: Research methodology

This chapter briefly describes the methodologies adopted to answer the research questions in this study.

Chapter 5: Results and discussions

This section presents the findings and discussions of the mineralogy, major and trace element concentrations, pollution level and sources of trace elements in soil and road dust. Human health risks associated with trace elements in soil and road dust are also presented and discussed. Furthermore, health implications are addressed.

Chapter 6: Conclusions and recommendations

The final chapter draws a conclusion based on the current findings. Furthermore, proper recommendation and future studies are also outlined.

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CHAPTER 2

LITERATURE REVIEW

Geochemical impact of urban informal settlements in developing countries on environmental sustainability: An overview

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Abstract

The urban landscape of most developing countries has experienced a manifestation of informal settlements for many years. The majority of those informal settlements are unsustainable and continue to cause detrimental impacts on the environment. Large populations in informal settlements contribute to a huge waste proliferation that results in land contamination and discharge of chemicals to the surrounding environment. Heavy metals are discharged via sources such as household heating, burning of coal and oil, transport, industrial processes, burning of waste, construction, weathering and maintenance of roads. Waste disposal of foodstuff, petroleum, cosmetic products, medications, and personal care also influence the proliferation of trace elements in informal settlements. Heavy metals such as Cd, Co, Cr, Cu, Mo, Ni, Pb and Zn normally accumulate in urban environments. When heavy metal concentrations surpass a specified limit, they affect the surrounding area and threaten the health of human beings. Provision of water and proper sanitation, the use of alternative clean-burning energy sources, supply of extra refuse containers avoiding burning of waste, community servicing, better communication and education, increasing the green gross domestic product, reducing heavy metals in fuel and utilising renewable energies, may reduce heavy metal pollution in informal settlements, thus making them sustainable. Urban geochemistry is extremely significant in evaluating environmental and health risks of urban soil pollution and decision-making in urban planning and sustainable development. This chapter therefore presents a brief overview of the geochemical impact of urban informal settlements in developing countries on environmental sustainability.

Keywords: urban; informal settlement; geochemical; developing countries; environmental sustainability; heavy metals

2.1 Introduction

The greatest challenges of the twenty-first century is urbanisation. Approximately 68% of the global population is expected to reside in metropolitan areas by 2050 (United Nations 2018; Parikh et al. 2020). Informal settlements are the most important part of urban areas worldwide as a result of rapid urbanisation and the growing population (Marutlulle 2017; Parikh et al. 2020). The majority of urban landscapes in developing nations have experienced the manifestation of informal settlements for many years. As urban areas expand, informal settlement areas also escalate. The number of informal settlement areas escalate due to the incessant movement of people to the metropolitan areas in pursuit of better opportunities and means of supporting themselves (Msimang 2017).

Nearly one billion or 32% of the global urban population reside in informal settlements and most of them in developing countries (Salman et al. 2011). According to Parikh et al. (2020), informal settlements in developing nations are home to over half of the urban poor, and in African metropolises, it accommodates approximately 61.7% of the urban population (Parikh et al. 2020). Salman et al. (2011) emphasised that if no stern act is taken, the quantity of informal settlement residents universally will escalate to two billion over the next 30 years (Salman et al. 2011).

Large populations in informal settlements, coupled with ongoing poverty as well as lack of basic necessities for an adequate lifestyle, inflict a huge challenge for sustainable development (Menshawy et al. 2011). Generally, informal settlements are considered to be unplanned and unserviced (Abbott 2000). According to Msimang (2017), informal settlements are an appalling development of the consequences of poverty and inherited inequalities. The deficiency of resistant and satisfactory structures in informal settlements, together with poor accommodation standards in extremely populated locations, prominently intensify the possibility of infections and harm (Parikh et al. 2020; Satterthwaite 2017). Most of the informal settlements are unsustainable and continue to cause detrimental effects on the environment. Their environmental effects are severe and result in life-threatening damages for the future (Hansen et al. 2005).

Several publicised studies have found that this extreme geographic changes will cause stern challenges to the quality of the environment and health of human beings

(Msimang 2017; Thomas 2001). Industrial activities, traffic flow, as well as energy production, have caused exposure to air pollution due to industrialisation and the demand for improved quality of life. Sebaiwa (2016) indicated that the air we inhale has been polluted by natural and anthropogenic activities mostly in developing nations as a result of urbanisation and industrialisation. Furthermore, urban development has seriously impacted land cover, land use and also altered the biogeochemical cycles of most elements (Chambers et al. 2016).

On a daily basis, several man-made activities such as commercial, agricultural, municipal and industrial activities, discharge a range of harmful contaminants into the environment (Nriagu 1996). In urban environments, these activities are extreme, and as a result, discharge of both inorganic and organic contaminants are habitually extremely accelerated, making the urban environment prone to environmental degradation and pollution (Thornton 1993). The formation of informal settlements also affect the environment negatively and impose health risks to human beings (Hansen et al. 2005). Informal settlement challenges range from soil, water or air pollution, waste pollution, poor land use and global warming (Msimang 2017).

Furthermore, due to the large populations in one area, waste is discarded randomly, leading to the discharge of chemicals to the surrounding environment (Msimang 2017). Urban informal settlements increase the concentration of major and trace elements through activities such as transport, household heating, combustion of coal and oil, burning of waste, industrial processes, construction, road weathering and maintenance (Charlesworth et al. 2011). Waste disposal of cosmetic products, medications, foodstuff, petroleum and personal care products also contributes to the build-up of heavy metals in informal settlements (Singo 2013).

Some of the heavy metals commonly released in urban environments are cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), zinc (Zn) (Gabarrón et al. 2017; Lu et al. 2003; Widinarco et al. 2000). When the concentration of heavy metals surpasses the recommended limits, they turn out to be harmful to the surrounding areas and threaten the health of human beings. The linkage between the natural environment and people is one of interdependence. The natural environment is of paramount importance for the existence of humanity and the one cannot exist without the other (Newaz et al. 2020). In informal settlements, the accumulation of heavy

Central University of Technology, Free State

metals may be reduced by the provision of water and proper sanitation, the use of alternative clean-burning energy sources, supply of extra refuse containers, avoiding burning of waste, community servicing, better communication and education (Muchapondwa 2010). Furthermore, increasing the green gross domestic product (GDP), minimising heavy metals in fuel and using renewable energies (Hu et al. 2014) may play a vital role in reducing heavy metal pollution in informal settlements, thus making it sustainable.

For several years, accomplishing environmental sustainability has been a world-wide challenge (Soyinka and Siu 2017). Information about the characteristics, size, and spatial distribution of human populations in informal settlements is vital in understanding its geochemical impacts and for competent urban planning and policy development (Lowry and Lowry 2014; Mottelson 2020) for environmental sustainability. This review chapter aims at shedding light on the geochemical impact of urban informal settlements in developing countries on environmental sustainability.

2.2 Urban settlement and urbanisation

An improved area to accommodate a large number of human populations, which a natural system is typically unable to provide, is called an urban setting or area. Dense population, an extensive paved network, high density transport systems, above and underground infrastructure, as well as a relatively high production level, are some of the unique features of a common urban settlement. These unique features are only conceivable through extensive physical modifications to the natural environment. Consequently, these alterations give rise to biological, chemical and physical features that make urban areas dissimilar from a natural ecosystem (De Kimpe and Morel 2000). The Centre of Expertise for Urban Programming (2016) defined an urban setting as based on population size, concentration of administrative bodies, infra-structure and different sets of livelihoods as well as income-generation activities.

Urbanisation simply means the removal of the natural ecosystem. The ongoing progression of development, use, as well as replenishment of urban infrastructures leads to extreme higher rates of transformation in urban surroundings than it is common elsewhere (Sager 2020). Furthermore, urbanisation is the physical development of urban areas due to rural relocation and even suburban concentration

Central University of Technology, Free State

into cities, mostly the biggest one. It is interrelated to modernisation, industrialisation, and the sociological process of rationalisation. Urbanisation is not just a modern process, but a quick change of human social roots on a global scale, where village custom is being quickly substituted by the urban principles (Jhawar et al. 2012). The surroundings of the urban areas differ from one urban area to another, subject to the urban structure, distribution of vehicles and fuel types used. Park soils, garden soils, roadside soils, and fallows are also found in urban areas (Rodriguez-Seijo 2017; Sager 2020).

In both developing and developed countries, rural–urban movement is a constant phenomenon (Msimang 2017). Today, urban areas are labelled as sprawling areas that are connected in a dendritic manner. The positive characteristics of urbanisation have frequently been surpassed by deterioration in the physical environment and life quality, triggered by the huge gaps between supply and demand for important amenities and infrastructure. Urbanisation happens when the burden on the land is high, agricultural income is low and population increases are extreme, just like the circumstances in most developing countries. Urbanisation has become not only of the primary display but also a force of change, and the hub of an urban switch for human society. Urbanisation is necessary for humanity's improvement. However, it has been accountable for various issues, resulting in a poor living environment, water, noise and air pollution, waste accumulation and traffic congestion (Jhawar et al. 2012).

2.3 Characteristics of informal settlements in developing countries

According to Abbott (2002a), an informal settlement has two interconnected sides. The first side concentrates on the natural environment and settlement infrastructures, whereas the other side pays attention to populations and their socio-economic status (Abbott 2002a; Msimang 2017). Informal settlements are defined as derelict portions of cities where accommodation and living conditions are dreadfully deficient. They range from highly populated, unclean central city dwellings to unplanned squatter sites spreading at the edge of cities, with no legitimate rights. Some have been established for more than 50 years, while others are invasions of land in progress (Menshawy et al. 2011). They are mostly characterised by informal land lease, insufficient supply of basic services, and poor infrastructure. Furthermore, informal settlements are characterised by the absence of a secure lease, infrastructures that go against municipal by-laws, housing constructed on private land, poor accommodation, illegal division of buildings, poverty, crime, social marginalisation, unhealthy living environments and risky settings (Amao 2012).

2.4 Urban geochemistry and environmental sustainability

The number of people living in urban environment has dramatically increased globally over the past years. Approximately 6.3 billion persons will be residing in urban settings by 2050 (Chambers et al. 2016; United Nations 2015). The growth of the population in urban areas directly impact land use, land cover, and change the biogeochemical cycles of most elements (Chambers et al. 2016; Wayland et al. 2003). Urban geochemistry focuses on the interactions and connections between chemical elements and compounds in the urban areas. Furthermore, it is concerned with the effect of historical and present-day anthropogenic activities and the effects of geochemical parameters on plants, animals and people's health (Chambers et al. 2016; Thornton 1991).

Given that natural resources encompass the majority of raw materials that are managed for human support, the general geochemical signature of urban environments is like that of the lithosphere, which is characterised by silicates and carbonates. However, urban areas are different from the lithosphere in that (1) natural materials have been changed chemically and physically to realise the preferred features for usage in urban infrastructure and processes; (2) various assortments of earth materials and synthetic materials exist in restricted geographic areas; (3) materials are suddenly positioned in new environments where they mix with both natural and anthropogenic materials; and (4) many elements and chemical compounds are presented into the urban environment at higher concentrations than at natural background level. Consequently, urban geochemical cycles are disturbed by the introduction of foreign materials and the discharge of elements and compounds from anthropogenic activities (De Vos et al. 2002; Kolpin et al. 2004).

Urbanisation contributes to dispersion of heavy metals throughout the world, contaminating it and destroying pristine environments for coming generations. The manner in which the present world is developing is unsustainable (Pawłowski 2008, 2009a). This is a clear indication that the present generation is existing at the expense of the next generations (Udo and Pawłowski 2010). Environmental sustainability is regarded as the capability of the biophysical environment to sustain its functioning over time within natural factors and series, in order to supply environmental goods and services to the economic and social domains. According to Yavuz (2016), sustainability is the continuing function of an ecosystem or use of a resource and indicates stable demands (Yavuz 2016). The natural environment is considered as sustainable when it can handle with and recuperate from stresses and shocks (Nassar and Elsayed 2017). Therefore, for the urban environment to be able to survive and recuperate from stress and shocks, urban geochemistry should be taken into consideration at a wide range of scales with regard to the various compartments of the urban system, such as soils, subsoils, the deeper subsurface, groundwater, sediments and air (Guern 2017).

Urban geochemistry is a critical component of urban management, development and planning. It assists to understand the urban geochemical signatures and dynamics, identify the legacy of affected hydrologic and geochemical cycles in urban locations. It also measures the urban geochemical signature, comprehends the influence of urban settings on geochemical cycles as a result of the incessant development and deterioration of physical infrastructure and relates them to human and environmental health (Chambers et al*.* 2016). Furthermore, an understanding of urban geochemistry helps to reflect on urban soil pollution. Urban geochemistry is mainly useful in the earlier phases of urban planning and during renovation. During the planning phase, it ensures that development is not done in a heavily polluted and harmful environment. During renovation projects, it is vital in anticipating pollution problems if unnecessary costs, interruptions, and adverse public relations are to be evaded (Guern 2017).

Land usages related to urban development leave a legacy of pollution that is only discovered at a later stage (Chambers et al. 2016; Colten 1994). These effects of pollution should be recognised in order to develop strategies to counteract or reduce human and ecosystem exposure to harmful materials. In order to recognise geo-chemical characteristics, geochemistry should be introduced into discussions on future urban planning. In addition to expecting future geochemical impacts, knowing both the past and present human geochemical effect on the environment is a key

Central University of Technology, Free State

aspect of urban geochemical studies (Chambers et al. 2016) and achieving environmental sustainability.

2.5 Geochemical investigation methods

2.5.1 Particulate

Particles differ considerably with size, that is, from few nanometres (nm) to tens of micrometres (µm) in diameter. An important characteristic of particles is size that helps in defining the atmospheric period and effects on light scattering (Sebaiwa 2016). Sebaiwa (2016) reported that the distribution of atmospheric aerosol size plays a vital role in broadly understanding their movement, elimination and origin. Vallius (2005) further stressed that size is particularly the most important factor of the characteristics of particles and it has effects on alteration, physical and chemical properties, movement, and elimination of particles from the air. The behavioural arrangement and inhabitant period of atmospheric particles are dependent on size and further offer mechanisms that increases the particles (Sebaiwa 2016; Seinfeld and Pandis 1998).

The particle mass size distribution information is typically described by the following particle modes: nucleation ($D_p < 0.01$ µm), Aitken ($D_p < 0.1$ µm), accumulation (0.1 µm $< D_p <$ 1.0 µm) and coarse ($D_p >$ 1.0 µm) (Finlayson-Pitts and Pitts 2000; Sebaiwa 2016). These ways rely mainly on various sources, mechanisms of creation and chemical composition. The change of particle size distribution in the air occurs over the courses of new particle formation, growth, evaporation and removal (Hinds 1999; Sebaiwa 2016). Particles are commonly categorised into fine and coarse particles (Sebaiwa 2016).

2.5.1.1 Coarse particulate matter

According to Sebaiwa (2016), particles with an aerodynamic diameter of between 2.5 and 10 µm are regarded as coarse particulate matter (PM_{10}). Coarse particulate matter is formed from mechanical disruption such as crushing and suspension of dust. This type of particles are of both anthropogenic and from natural sources. They contain materials such as leaf litter decay, pollen, spores and viruses (Scott 2010; Sebaiwa 2016). Coarse particles do not stay in the air for long as they are removed quickly due to high sedimentation. The lifespan of coarse particulate matter ranges from minutes to hours, and it travel a distance of < 1 km to 10 km (Sebaiwa 2016).

2.5.1.2 Fine particulate matter

Fine particulate matter ($PM_{2.5}$) with an aerodynamic diameter of less than 2.5 μm is regarded as fine. Fine particles are formed from gas and condensation of high temperature vapours during combustion. They are characterised by various mixtures such as sulphate compounds, nitrate, carbon compounds, ammonium, and hydrogen ion. Crist et al. (2008) and Sebaiwa (2016) stated that most of $PM_{2.5}$ components are materials resulting right from chemical reactions of sulphur dioxide (SO_2), nitric oxide and nitrogen dioxide (NOx), volatile organic compounds, elemental carbon and a number of heavy metals. Their lifespan is from days to weeks and can travel a distance of hundreds to more than a thousand kilometres (Sebaiwa 2016). Fine particles can stay in the air for a long time and are eventually removed by the process of settling or raining out. The increase of fine particles in the atmosphere reduces visibility (Krupa et al. 2001; Sebaiwa 2016).

2.5.2 Road dust

Dust is regarded as tiny, dry, solid particles suspended in the atmosphere as a result of natural or man-made processes and typically occurs in particle sizes that range from 1 μm to 100 μm in diameter (International Union of Pure and Applied Chemistry 1990; Sepadi 2019). Also, it is finely divided solids that may become airborne from the original state with no chemical or physical change, except fracture (Sepadi 2019). In addition, Ji and Huang (2008) generally defined dust as the particulate matter lying on the surface of the earth that can be resuspended in air and scatters prior to its return to earth (see also Sebaiwa 2016).

Specifically, the term *road dust* refers to resuspended particulate matter found on roads, mostly in troughs. Road dust mainly contains soil and sand particles that are mixed with litter and larger amounts of debris that become airborne due to disturbance by vehicles (Calvillo 2015; Sampson 2017). The quantity of road dust is determined by factors such as soil type, weather and sweeping of roads. Its particle sizes also differ from coarser particles to finer particles. As a result of road abrasion, wear and friction of vehicle parts, road dust may be enriched with high concentrations of heavy metals (Kennedy 2003; Sampson 2017). Characterisation of size and forms of dust play a crucial role in understanding its implications for human health (Sebaiwa 2016).

The classification of dust is based on its effects, which include environmental, occupational health and physiological effects (Petavratzi et al. 2005; Sebaiwa 2016).

2.5.2.1 Environmental effects

This is the class that encompasses generated, total suspended, nuisance and fugitive dust. Dust that originates from solid material broken down into tiny particles due to mechanical processes such as cutting, boring, crushing and clearing is called generated dust (Safety in Mines Research Advisory Committee [SIMRAC] 2003; Sebaiwa 2016). During mechanical processes, small particles are suspended into the air and can stay suspended for a long period or could stick to each other, and as a result, they grow in size as well as density and fall to the ground because of gravity. Dust floating in the atmosphere is regarded as total suspended dust. Dust that reduces visibility, causes nasal irritation, respiratory irritation and stains buildings is called nuisance dust (Petavratzi et al. 2005; Sebaiwa 2016). Fugitive dust is nontoxic dust produced from a non-point source. However, its collaboration with other air contaminants may have detrimental effects on human health. It is the outcome of mechanical disruption of coarse material (Sebaiwa 2016; United States Environmental Protection Agency [USEPA] 2015). Fugitive dust may be generated from aggregate storage piles, agricultural tilling operations, unpaved roads and heavy construction operations (Kentucky Division for Air Quality 2014; Sebaiwa 2016).

2.5.2.2 Occupational health effects

Occupational health effects encompass inhalable, thoracic and respirable dust. Inhalable dust is defined as the fraction of dust with an aerodynamic diameter of less than 20 μm that may enter through a person’s nose and mouth during the process of respiration and end up in the respiratory tract (Sebaiwa 2016; SIMRAC 2003). Thoracic dust is defined as dust with particle sizes that have the ability to reach the tracheobronchial area and gas exchange area for deposition (Selenati-Dreyer 2010; Sebaiwa 2016). Finally, respirable dust fractions are less than 10 μm and have the ability to enter the gas exchange area of the lung (Petavratzi et al. 2005; Sebaiwa 2016).

2.5.2.3 Physiological and physical effects

The physiological effect class is characterised by toxic, carcinogenic and fibrogenic dust. Toxic dust has the ability to start chemical reactions within the respiratory tract or permit assimilation of toxic material into the bloodstream through the alveolar walls (Sebaiwa 2016; SIMRAC 2003). Cancer-causing dust may originate from asbestos, uranium, arsenic or quartz. According to SIMRAC (2003) and Sebaiwa (2016), it may cause the microscopic damaging of lung tissue, which may lead to the development of a fibrous growth, loss of lung elasticity as well as a large reduction in the gas exchange area. Fibrous dusts may have health implications mainly associated with the shape of the particles which include dust from asbestos (Sebaiwa 2016; World Health Organization 1997;).

2.5.3 Heavy metals

Any metallic element that is toxic is regarded as a heavy metal (Duruibe et al. 2007; Lenntech Water Treatment and Air Purification 2004). Metals and metalloids with an atomic density of more than 5 g/cm^{-3} and an atomic mass that is higher than 40, are considered to be heavy metals (Duruibe et al. 2007). Furthermore, heavy metals cannot be degraded or destroyed (Timothy and Williams 2019). Out of all 90 naturally occurring elements, 53 are considered to be heavy metals. Among them, iron, molybdenum and manganese are vital as micronutrients. Zinc (Zn), nickel (Ni), copper (Cu), cobalt (Co) and chromium (Cr) are considered toxic elements which are also vital as trace elements. Silver (Ag), arsenic (As), mercury (Hg), cadmium (Cd), antimony (Sb) and lead (Pb) have no known function as nutrients and are toxic to plants and microorganism.

Elements that are persistent in all parts of the environment and of highest concern among the public are tin (Sn), thallium (Tl), Cr, Ni, Hg, Mn, Cd, Co, Cu and Pb (Timothy and Williams 2019; Zhang et al. 2012). Heavy metals are found in different forms such as phosphates, oxides, silicates, hydroxides, sulphides, sulphates and organic compounds. When they are not metabolised by the body, they mount up in the soft tissues and as a result, they turn out to be toxic to human and animal health (Masindi and Muedi 2018). Furthermore, heavy metals in soil may be found in many forms such as dissolved, exchangeable, as structural components of the lattices of soil minerals and as insoluble precipitates with other soil components (Aydinalp and Marinova 2003).

2.6 Sources and pathways for heavy metals in informal settlements

From the time of earth's formation, heavy metals originate naturally on earth (Briffa et al. 2020). However, the industrialisation has intensely accelerated the load of heavy metals on earth (Singo 2013). The main sources of heavy metal pollution on earth are natural and anthropogenic sources (Solgi et al. 2014).

2.6.1 Natural sources

Natural sources of heavy metals into the environment are volcanic eruptions, rock weathering, forest fires, biogenic sources, sea-salt sprays and wind-borne soil particles (Herawati et al. 2000; Masindi and Muedi 2018). Volcanic activity (such as geothermal activity or magma degassing), continental weathering and forest fires contributes more to the release of heavy metals into the environment (air, soil and water) (Naggar et al. 2018). Heavy metals such as Cu, Hg, Pb, As, Cr, Cd, An and Ni are mostly released naturally. Although heavy metals released naturally are found in traces, they have the potential to cause medical problems to human beings and mammals (Herawati et al. 2000; Masindi and Muedi 2018).

2.6.2 Anthropogenic sources and urbanisation

The release of metal pollution from human activities include industrial and medical waste (Dorigo et al. 2004; Jackson et al. 2007), pesticides, petroleum by-products (Mowat and Bundy 2001), household products, as well as urban and pharmaceutical waste (Brooks et al. 2003; Jackson et al. 2007). According to Jackson et al. (2007), domestic and household sources of metal pollution commonly happen as a result of deterioration of metal plumbing fittings, galvanised roofs and wire fences, health care products, shampoos, baby creams, silver paint, saucepans and utensils. They contribute significantly to the release of heavy metals such as Zn, Cd, selenium (Se) and aluminium (Al) (Jackson et al. 2007). The release of pollutants to different environmental sections may also be contributed by activities such as agriculture, mining, industries, wastewater, metallurgical processes and runoffs. As the populations in urban areas increase continuously, their influence on environmental pollution also increases (Charlesworth et al. 2011). This can be attributed to sources such as traffic, household heating, combustion of coal and oil, resuspension of soil, street dust particles and other sources.

2.6.2.1 Traffic

In the past, traffic sources have released huge volumes of lead to the atmosphere from the use of leaded petrol (Charlesworth et al. 2011; Kowalczyk et al. 1982). Globally, vehicle catalytic converters also contribute to the release of platinum group elements or metals which include platinum (Pt), palladium (Pd), rodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os), in the environment (Ravindra et al. 2004). The rate of Pt deposition in urban environment may reach 23 ng/m^{-2}/day^{-1} (Barbante et al. 2001; Charlesworth et al. 2011; Schäfer et al. 1999). These elements bioaccumulate (Palacios et al. 2000) and are also conveyed as ultrafine, inhalable particle sizes, commonly < 0.39 μm (Charlesworth et al. 2011).

2.6.2.2 Domestic heating, combustion of coal and oil

Historically, combustion of coal has been one of the sources that releases Mn, Cr, Cu, Co, As and Se. However, its precise emission profile is influenced by the kind of coal burnt. Vanadium (V), Ni and sulphur (S) have been practically commonly utilised as tracers of oil combustion (Charlesworth et al. 2011).

2.6.2.3 Resuspension of soil and street dust particles

Soil and street dust particles can be transported into the air by wind currents where they represent an important amount of its coarse fraction. Although wind is obviously significant, vehicles and pedestrians, agricultural activities, street sweeping and construction operations can also contribute to the release of particles into the air (Charlesworth et al. 2011; Patra et al. 2008). Soil resuspension is possibly the key source of potassium (K), magnesium (Mg) and manganese (Mn). However, together with combustion of coal, offers a significant quantity of aluminium (Al), calcium (Ca), cerium (Ce), Cr, Fe, lanthanum (La), scandium (Sc), strontium (Sr), titanium (Ti) and thorium (Th). Fine soil and street dust fractions are enriched with heavy metals as a result of anthropogenic activities, when re-suspended, can contribute to inhalable trace element load of an urban aerosol (Charlesworth et al. 2011).

2.6.2.4 Other urban sources

Other urban sources may include man-made activities such as:

- specific burning of waste;
- industrial processes;
- construction activities;
- weathering of roads; and
- maintenance of roads (Charlesworth et al. 2011).

2.7 Environmental sustainability of urban informal settlements

Most of the informal settlements are illegal, unplanned, unstructured and have been developed in areas that are not appropriate for housing purposes (Msimang 2017). Open or unprotected spaces adjacent to the poorest parts of the formal towns are thus the most vulnerable to new developments of informal settlements (Chikoto 2009). Informal settlements are unsustainable and impacts the environment negatively. These areas are unplanned, have no impact assessment done before construction and the materials used are not of housing standards. All these lead to informal housing and unsustainable development (Msimang 2017). Furthermore, informal settlement inhabitants engage in practices that are hostile to the environment. They discard waste randomly, construct housing as and where they want and contaminate their surrounding environment without remorse (Msimang 2017).

According to Napier (2007), the development of informal settlements lead to a damage of natural vegetation, biodiversity and has an impact on ecosystems, which support human beings. Cutting of trees for informal housing affect the quality of soil and leads to soil erosion. The eroded soil ends up polluting water and rising the expense of water purification systems (Msimang 2017; Napier 2007). Furthermore, the use of fossil fuels by the majority of informal settlers contribute to air pollution (Mahlakoana 2010; Msimang 2017; Napier 2007). Areas are considered sustainable when they can handle with and recuperate from stresses and shocks, consequently informal settlements are unsustainable as they cannot handle with and recuperate from the stresses and shocks they are facing (Nassar and Elsayed 2017).

2.7.1 Health effects on human

Most of the informal settlements are deprived of water supply and sanitation. Such conditions create a situation that contributes to risks of infectious diseases such as waterborne and vector-borne diseases (World Health Organization 2008; Zerbo et al. 2020). Furthermore, informal settlements most of the time create conditions favourable for cholera outbreaks (Rebaudet 2013; Zerbo et al. 2020). Huge piles of waste in informal settlements are home for nurturing parasites and transmitting diseases. Globally, the *Aedes* mosquitoes in informal settlement areas expose the inhabitants to dengue fever and emerging infectious diseases. In addition, overpopulation is a breeding ground for the spreading of tuberculosis and spreading of the Ebola virus disease and increases the incidence of the human immunodeficiency virus (HIV) (Zerbo et al. 2020). The use of nearby waterways can expose inhabitants of informal settlements to chemicals due to the surface runoff from the settlements, leading to severe health implications, such as *bacillary* dysentery and cholera in some cases, and even cancer in areas with rivers polluted by uranium (U) and As (Abia et al. 2016, 2018; Marara et al. 2013; Ngole-Jeme and Fantke 2017; Weimann and Oni 2019).

2.7.2 Economic effects

Unemployment and poverty are some of the characteristics seen in informal settle-ments. All these factors lead to human tragedies, prostitution, abuse of substance and illegal activities. In order to feed their families, the majority of inhabitants in informal settlements rely on informal activities, as job opportunities are few and require education which most of the dwellers do not possess (Msimang 2017). In a report on self-made cities, the United Nations Economic Commission for Europe (2009), mentioned informal settlements residents are poor, jobless, experience social hardships and tenure insecurity. They generally do not have security or housing tenure and face threats of eviction.

Central University of Technology, Free State

2.7.3 Psychological effect

Poverty as well as low socio-economic status have the potential to raise stress and feelings of depression (Smit et al. 2006; Weimann and Oni 2019). Psychosocial health problems are a major cause of morbidity and mortality among teenage and young adults in most low-income countries. The majority of children living in informal settlements have been noticed to have various behavioural and emotional problems. The chance to have stress and psychological disorders is high in informal settlements due to stressful life and working conditions. Depression, alcohol abuse, drug, suicide, and violence are psychosocial health problems that dominate many informal settlements. The poor housing quality, living environment and non-environmental factors lead to stress, which is the underlying cause of many psychosocial disorders (Zerbo et al. 2020).

2.8 Minimisation of heavy metal pollution in informal settlements

Globally, environmental protection has become a significant norm in order to support humans. Informal settlement proliferation in the developing world is of great concern because of its negative impacts on the environment and quality of life. Some of the ways to minimise heavy metal pollution in informal settlements include the following:

- **Provision of water and proper sanitation:** Sanitation and water supplies are often inadequate in informal settlements. Delivery of adequate sanitation, waste removal facilities and piped water may minimise the discharge of toxic chemicals that affect the environment and quality of life.
- **The use of alternative clean-burning energy sources:** The majority of informal settlers extensively use wood and charcoal for cooking. Wood or charcoal used by the informal settlers should be substituted with clean-burning energy sources. Possible options include the use of electricity and gas. Improved wood-burning technology may also reduce the release of heavy metals (Muchapondwa 2010).
- **Supply of additional refuse containers:** The provision of containers for domestic waste may decrease waste pollution in informal settlements. Households in informal settlements should also be provided with refuse bags for storing waste before discarding it in the containers (Muchapondwa 2010).

- **Avoiding burning of waste:** Waste incineration may make the resulting PM_{10} pollution very serious. Supply of additional waste containers to be located at the areas where waste incineration has been noticed may reduce the burning of waste (Muchapondwa 2010).
- **Community servicing:** Planning of community servicing on a rotational basis as a way to include communities to collect and manage their waste through recycling and reuse, may reduce heavy metal pollution and create incomes for the communities.
- **Better communication and education**: Improved community communication and education about the importance of the environment, waste management and health may play a crucial role in minimising heavy metal pollution (Muchapondwa 2010). Residents should be educated and encouraged to accept the guidelines that regulate waste management.
- **Increasing the green GDP:** To increase green GDP, particularly in polluted areas, government should prioritise research programmes that cover areas such as cleaner production and the environmental protection industry; clean energy, green transport and buildings; conservation and sustainable utilisation of natural resources; pollution control technology for waste gas; waste water and solid wastes; and public health and human settlements as a means to minimise heavy metal pollution (Hu et al. 2014).
- **Reducing heavy metals in fuel:** Burning of fuel in vehicles releases heavy metals to the atmosphere. Gasoline with less lead should be required for new cars because the lead also damages the catalytic converter that is used to control other pollutants derived from automobile exhaust (Hu et al. 2014).
- **Utilising renewable energies:** Development of renewable energies to lower the percentage of coal in energy consumption may also minimise heavy metal pollution. This can be achieved by introducing regulations that favour generation and marketisation of renewable energy; making renewable energies to become more cost competitive by providing new technologies to power producers; establishing financial support frameworks to increase renewable and clean energies use, especially for solar power, wind power and shale gas (Hu et al. 2014).

2.9 Conclusion

Most of the informal settlements are illegal, unplanned, unstructured and have been developed in areas which are not suitable for housing purposes. They are unsustainable and impact the environment negatively. As informal settlement populations grow, their contribution to environmental pollution also increases. Sources such as transport, household heating, combustion of coal and oil, industrial processes, burning of waste, construction activities, weathering of roads and maintenance of roads, cosmetic products, pharmaceutical waste, foodstuff, petroleum and personal care contribute to the accumulation of heavy metals in urban informal settlements making them susceptible to environmental degradation and contamination. Provision of water and proper sanitation, the use of alternative clean-burning energy sources, supply of refuse containers, avoiding burning of waste, community servicing, better communication and education play a vital role in the minimisation of heavy metals. Furthermore, increasing the green GDP, reducing heavy metals in fuel and utilising renewable energies may also reduce pollution in informal settlement, thus making it more sustainable. Urban geochemistry is highly relevant in assessing environmental and health risks of urban soil pollution and decision-making in urban planning and sustainable development.

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CHAPTER 3

BACKGROUND OF THE STUDY AREA

3.1 Introduction

This chapter provides a detailed description of the study area. It covers aspects such as study setting, population, status of the physical environment, status of the infrastructure and socio-economic conditions. Furthermore, the integration and sustainability of the Winnie Mandela informal settlement will also be described. This area was carefully chosen for the study because little or no data were available on the concentration of heavy metals in soil and road dust in this settlement, which is a public health concern.

3.2 Study setting

According to Maseko (2016), a research setting is the area where a study is conducted. Furthermore, Polit and Beck (2010:568) defined a study setting as the physical location and condition in which data are gathered. Consequently, the research setting for this study was the Winnie Mandela informal settlement, situated within the township of Thembisa which falls under the Ekurhuleni Metropolitan Municipality in the Gauteng province, South Africa. The township was developed in 1957 at the time of apartheid, when Africans were relocated from Alexandra, Germiston, Kempton Park and Midrand (Makonese et al. 2016).

The Winnie Mandela informal settlement site is geographically situated at 26° 1’ 19” S and 28° 12’ 5” E. It is well located approximately 41 km north of Johannesburg and approximately 39.4 km south of Pretoria. Furthermore, the area is positioned 15 km north of the Kempton Park City Centre. It is accessible via the R21 regional road from Pretoria, the M39 or R24 from Johannesburg, and other roads such as the R562, also referred to as Olifantsfontein road (see Figure 3.1 for the locality map).

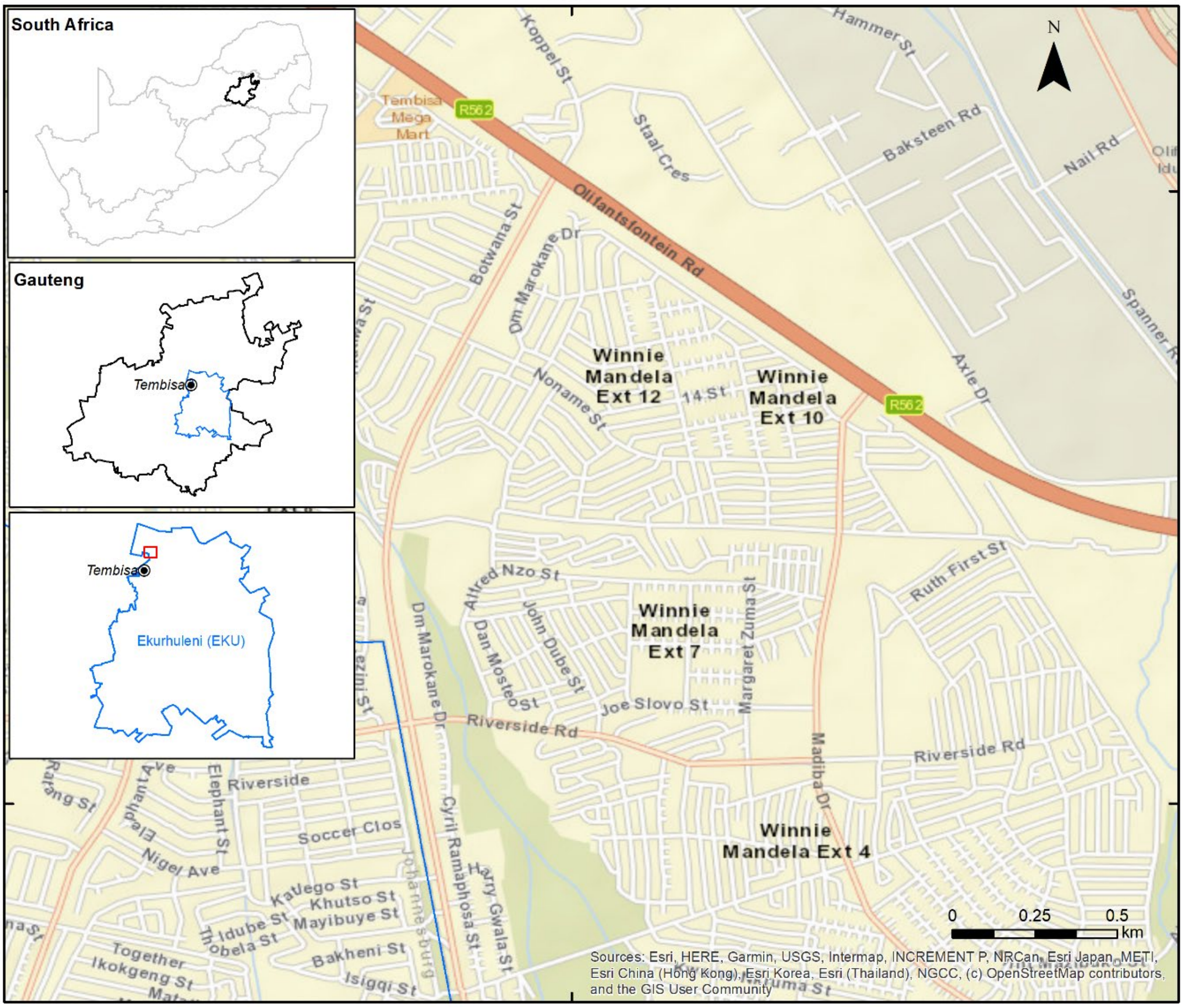

Figure 3.1 Locality map of Winnie Mandela informal settlement

3.3 Population

According to Statistics South Africa (2011), Winnie Mandela informal settlement consists of 41 581 households with a population of 91 646. It is dominated by approximately 99% of Black Africans in a surface area of 5.43 km^2. Asian, White and Coloured constitute 1% of the population. The settlement is mainly comprised of 58% males and 42% females (Figure 3.2). Furthermore, the highest percentage age group (18.78%) is between 25 and 29 years, as shown in Figure 3.3 (StatsSA 2011).

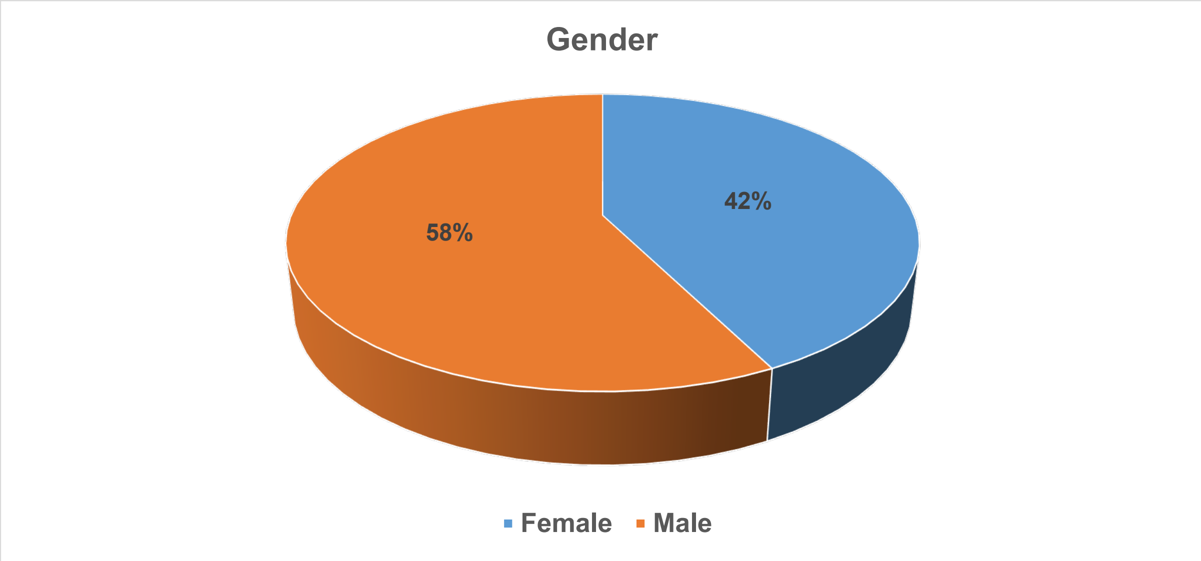

Figure 3.2 Winnie Mandela informal settlement gender distribution (StatsSA 2011)

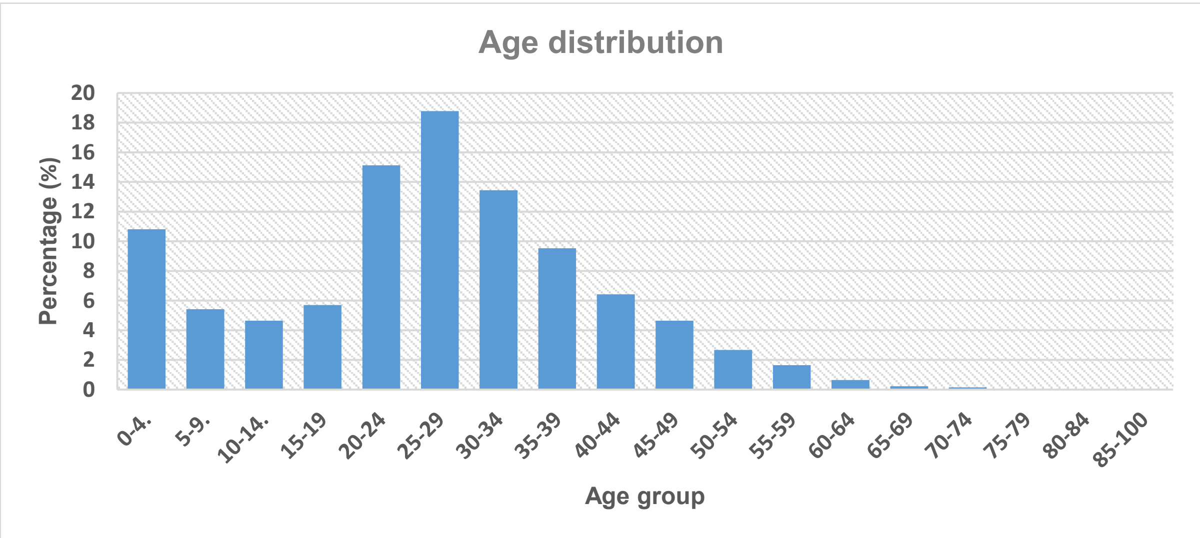

Figure 3.3 Winnie Mandela informal settlement age distribution (StatsSA 2011)

3.4 Status of the physical environment

3.4.1 Geology and soil

The area is underlain by Archean cratonic rocks allocated to the Johannesburg Dome, also recognised as the halfway house, or the Johannesburg–Pretoria Dome. The Johannesburg Dome is a dome-like window of ancient granitoid (approximately 750 km^2) in the area that is positioned in the middle part of the Kaapvaal Craton (Figure 3.4). It comprises of and tonalite–trondhjemite–granitic rocks intruded into mafic-ultramafic greenstones. After trondhjemite–tonalite gneisses emplacement, another period of magmatism created the mafic dykes intrusion that appears as hornblende-amphibolites. The period of the dyke took place during the time constraints forced by the era of the trondhjemite–gneiss (3 340–3 200 Ma), and afterwards it crosscut the potassic-granitoids (Roadlab 2014). The Johannesburg Dome consists of the following:

- An Archean granitoid dome consisting of tonalite–trondhjemite gneisses, banded gneiss, a foliated granodiorite zone and granodiorites.
- Remnants of the greenstone rocks distributed throughout the basement inlier.
- The Witwatersrand and Ventersdorp Supergroup rocks that are outcropping along the south-eastern margin and along the southern and south-western margins of the inlier, respectively.
- The black reef formation that forms the base of the Transvaal Supergroup, which outcrops to the north-eastern, northern and north-western margin of the inlier and unconformably overlies the granitoids and greenstones.
- The rocks assigned to the Witwatersrand and Ventersdorp Supergroup.
- The greenstone remnants dispersed throughout the basement inlier and are the oldest rocks of the Johannesburg Dome with an age of 3 750–2 870 Ma. They include the mafic and ultramafic rock altered to serpentinites, a variety of amphibolites and talc–chlorite carbonate schists.
- Foliated granodiorite which forms a transitional zone between the granodiorites (Roadlab 2014).

Furthermore, the study area is directly underlain by dolomite and chert with a north to south aligned syenite dyke located on the eastern boundary of the site. It is characterised by the blanketing layer which consists of colluviums, residual syenite, residual chert and dolomite with sub-areas consisting only of colluviums and residual syenite. Dolomite bedrock is also present at depths of between 7 m and 60 m (Lokisa Environmental Consulting 2018).

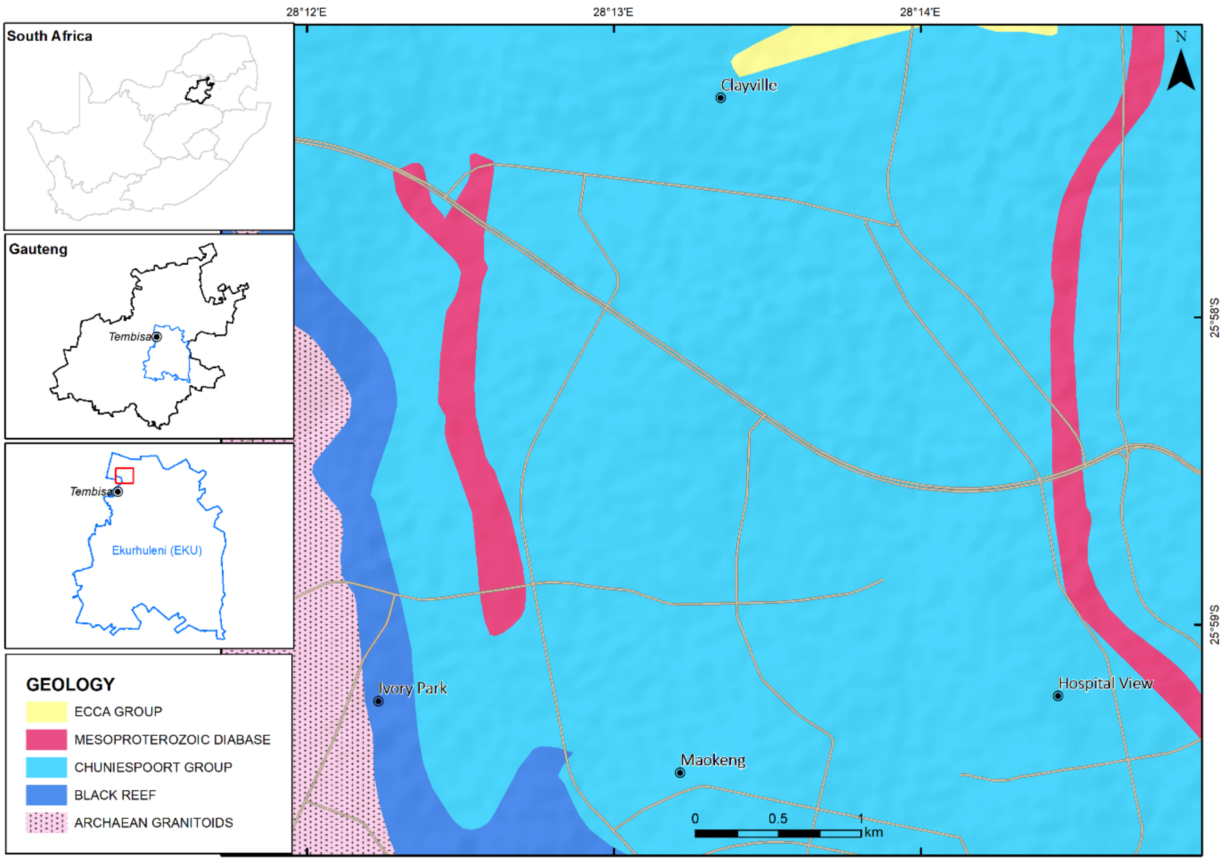

Figure 3.4 Geology of Winnie Mandela informal settlement

3.4.2 Climate

The area is characterised by a moderate Highveld climate with warm summers and mild winters. It experiences some rainfall mainly during summer. It is frequently characterised by a mean annual rainfall of 60 mm. January is considered to be the wettest month, with an average of approximately 125 mm. The month of July is the driest month, with an average of approximately 4 mm. Furthermore, the mean annual temperature is 16 °C, with January being the warmest at an average of 20.1 °C, whereas June is considered the coldest month at an average of 10.1 °C (Savannah Environmental 2018).

3.4.3 Wind condition

The wind within the area of the study is considered to be light to moderate. It is usually less than 8 m/s. However, the area do sometimes experience strong winds. The wind direction is generally west–northwest to east–northeast (Savannah Environmental 2018).

3.4.4 Topography

The Winnie Mandela informal settlement is located on the Highveld and has elevations varying between 1 540 m and 1 555 m above the mean sea level. It is moderately flat and slopes evenly in a south-westerly direction at an average slope ranging from 2−7% (Lokisa Environmental Consulting 2018).

3.4.5 Vegetation

The project area is situated in the grassland biome and dry Highveld grassland bio-region. The type of vegetation units within the study area are Eragrostis–Hyparthenia grassland, Eucalyptus–Crotalaria woodland, Amaranthus–Tagetes wasteland, drainage line vegetation and Eucalyptus–Zea mays informal fields (Lokisa Environmental Consulting 2018). However, at present, 98% of the area has already been transformed into a settlement area.

3.4.6 Air quality

To understand the quality of air in the area, characterisation of the concentration of current ambient contaminants and identification of their source of emissions is very important. Winnie Mandela informal settlement falls under the Ekurhuleni Metropolitan Municipality which covers an extensive area and is characterised by approximately 180 recorded industrial facilities. Traffic flow within the municipality is also noteworthy, with highway linkages to major cities such as Johannesburg, Pretoria and Durban (Savannah Environmental 2018).

Eleven ambient air quality monitoring stations, including one nearby the location called Olifantsfontein, are operated by the Winnie Mandela informal settlement. They collected data on contaminants such as sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and particulates on an hourly basis. Within the municipality, ambient particulate matter (PM_{10}) level surpasses the National Ambient Air Quality Standard (NAAQS). The municipality also experience frequent exceedance of NAAQS for NO_2. The annual average SO_2 concentrations at the Olifantsfontein monitoring station are under the NAAQS of 19 particles per billion (ppb) since 2014. The annual average NO_2 concentrations at Olifantsfontein are relatively high and exceeded the NAAQS of 19 ppb in 2014 and 2016.

Table 3.1 shows the annual mean concentrations of SO_2 and NO_2 at Olifantsfontein, measured in ppb (Savannah Environmental 2018). The concentration of SO_2 that exceed NAAQS of 19 ppb gives an idea that the quality of air within the area has been polluted by SO_2 and may have detrimental health implications to the local inhabitants. The source of contaminants may include the industrial area near the settlement, the use of charcoal, or motor vehicles. The sources of air pollution in Winnie Mandela informal settlement may possibly be from Clayville industrial activities, motor vehicles and other anthropogenic activities, such as waste incineration and charcoal burning.

Table 3.1 Annual average concentrations of nitrogen dioxide and sulphur dioxide (Savannah Environmental 2018)

Year	Nitrogen dioxide (particles per billion)	Sulphur dioxide (particles per billion)
2014	35.1	8.8
2015	–	5.3
2016	21.9	6.2
2017	12	4

3.5 Status of the infrastructure

According to Menshawya et al. (2011), informal settlements are characterised by poor environmental conditions such as overcrowding, unhealthy and poor living conditions, hazardous locations, poor quality of streets, presence of litter or unremoved garbage everywhere, and sewage water that is discharged most of the time over the ground in some areas. Winnie Mandela informal settlement is not an exception in this case as it possesses some of these features. Generally, Winnie Mandela informal settlement has many amenities and infrastructural challenges in terms of the following indicators:

3.5.1 Housing

In South Africa, accommodation is a serious issue and a number of citizens lack appropriate housing. Local municipalities are experiencing a problem of rapid proliferation of informal settlements that surpasses the development of new standard houses. The lack of proper housing provision for the poor urban dwellers by local administrations, elucidates the proliferation of informal settlements in South Africa (Chikoto 2009). As depicted in Figure 3.5, Winnie Mandela informal settlement is characterised by three different kinds of houses, which range from houses constructed informally with pieces of corrugated iron (called shacks); houses constructed with bricks and corrugated iron roofing in the Reconstruction and Development Programme (called RDP houses), as well as houses properly constructed with bricks and tiled roofing.

Shack RDP house Tiled House

Figure 3.5 Types of houses in Winnie Mandela informal settlement (Author's own, 2021)

3.5.2 Road network and trafficability

In any community, an appropriate road network is necessary for the transport circulation and convenience to different sections of the area. Consequently, appropriate streets or pathways are also essential in informal settlements (Chikoto 2009). In general, the road network of Winnie Mandela informal settlement can be divided into locally paved (tarred roads) and gravel or unpaved roads (Figure 3.6).

Tarred road Gravel road

Figure 3.6 Types of roads in Winnie Mandela informal settlement (Author's own 2021)

The community transport system functions with taxicabs which are the most used method of transport by inhabitants. High levels of traffic congestion are noteworthy during the early morning and late afternoon peak hours (Figure 3.7). High volumes of traffic is recorded on a locally paved road called Madiba Drive, with considerable volumes of vehicles noted in some minor streets.

Morning traffic

Afternoon traffic

Figure 3.7 High volume of traffic in in Winnie Mandela informal settlement (Author's own 2021)

3.5.3 Water and sanitation

In any location or area water is an essential commodity. It can be said that no water, no existence. All over the world, water is fundamentally utilised for consumption, food preparation, laundry, and bodily cleanliness (Chikoto 2009). Sanitation is also vital in any form of settlement. It normally denotes the supply of amenities for discarding human wastes safely. Sanitation has an important role, not only in the supply of health amenities but in the health of the general societies (Stephenson 2005). In informal settlements, proper provision of sanitation remains a serious problem. The city of Ekurhuleni has played a major role in ensuring that the settlement have a proper water supply and sanitation, although it remains a challenge. Quality water is supplied to the inhabitants by the district or local service supplier. Water is provided through pipes inside the houses and yards (Figure 3.8). Some parts of the settlement have proper sanitation in the form of flush toilets, whereas several areas are characterised by poor sanitation in the form of chemical toilets or pit toilets (Figure 3.9).

Figure 3.8 Source of water supply in Winnie Mandela informal settlement (Author's own 2021)

Flush toilet Pit toilet and chemical toilet

Figure 3.9 Sanitation in Winnie Mandela informal settlement (Author's own 2021)

3.5.4 Electricity and energy

The majority of the households within the settlement have been electrified (Figure 3.10). However, in some households, paraffin, charcoal and firewood are used as sources of energy. Affordability, accessibility, climate seasons and societal approval are some of the factors that determine the type of fuel to be used by residents (Makonese et al. 2016). Burning fossil fuels does not only contribute to the greenhouse gas concentrations, but also release chemicals that are detrimental to human health.

Figure 3.10 Electrified households in Winnie Mandela informal settlement (Author's own 2021)

3.5.5 Waste management

The process of collecting, transporting, handling, reprocessing or discarding and taking care of waste materials is regarded as waste management. In urban settings, management of non-toxic wastes from households and institutional areas is commonly the accountability of local municipalities. Furthermore, management of non-toxic waste from commercial and industrial areas is commonly the accountability of the producer (Chikoto 2009). The Ekurhuleni Metropolitan Municipality does provide waste management services to the community. Waste is collected once a week. However, some areas are characterised by littering and uncollected garbage as they are inaccessible, unplanned, illegal, have poor road conditions and high population density (Figure 3.11). Hence, cleanliness in this informal settlement remains a serious problem. Every open space within the settlement is likely to be used as a dumping area.

Figure 3.11 Uncollected garbage within Winnie Mandela informal settlement (Author's own, 2021)

3.6 Socio-economic condition of Winnie Mandela informal settlement

The City of Ekurhuleni is characterised by various economic sectors such as industrial, financial, commercial services, public services, general government, trade and hospitality sectors. Nevertheless, the rate of inequity and poverty is noteworthy within the city. Roughly 1.21 million persons or 35% of the society live in lack. The unemployment and crime rates are seriously high. Nearly 22% of the inhabitants live in informal areas with insufficient accommodation such as Winnie Mandela (City of Ekurhuleni, 2018).

Economic fluctuations in Winnie Mandela informal settlement is nominal and very slow. This is because most of the inhabitants live in lack with poor accommodation and a high rate of joblessness. Most of the commercial activities within the settlement have low-income amounts inadequate to save local residents from the poverty situation they are faced with. However, the area is situated approximately 2–3 km south of Clayville industrial area, which acts as source of employment for the residents. Furthermore, Phumulani Mall, local shops and some few petroleum stations are situated in proximity to the settlement, and they are also used as a source of employment.

3.7 Integration and sustainability

Most of the informal settlements are illegal, unplanned, unstructured and have been developed in an areas which are not appropriate for housing purposes (Msimang 2017). Some areas in Winnie Mandela informal settlement are planned, structured and sustainable, particularly those areas with planned RDP houses. The other sections are illegal, unplanned, unstructured and developed in areas not suitable for housing purposes. They are unsustainable and impacts the environment negatively. Physical observation of the area has demonstrated that inhabitants engage in practices that are hostile to the environment, such as discarding waste randomly, contaminating their surrounding environment without remorse and constructing houses as they want (Msimang, 2017). Their houses are built with materials that are not suitable for the construction of houses and no development plans or environmental impact assessments process are conducted in these areas prior to development.

Furthermore, inhabitants also use fossil fuel for cooking and warming during winter, which contribute to air pollution. According to Nassar and Elsayed (2017), areas are considered sustainable when they can handle with and recuperate from stresses and shocks. Therefore, Winnie Mandela informal settlement is unsustainable as it cannot handle with and recuperate from the stresses and shocks it is facing. According to Chikoto (2009), integrated improvement plans or practises require dependable and updated data on the social status of the community, which is difficult in informal settlements as their population rises on a daily basis. Furthermore, vacant spaces adjacent to the formal towns are being used for the development of informal settlements (Chikoto 2009).

3.8 Conclusions

Like any other informal settlement in the world, Winnie Mandela informal settlement has many services and infrastructural challenges that need to be addressed. Cleanliness in the settlement remains a challenge as every open space is used as a dumping site and those parts of areas that are unplanned, illegal and unsuitable for housing, pose negative impacts on the environment. Furthermore, sewage water that is discharged over the ground, the high population that leads to littering, as well as uncollected garbage within the area, may lead to possible release of trace elements which may have detrimental effects on the environment and human health. Indoor usage of fossil fuel by inhabitants for cooking and warming during winter also contributes to air pollution. Winnie Mandela informal settlement is unsustainable as it cannot deal with and recuperate from the stresses and shocks it is facing.

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CHAPTER 4
RESEARCH METHODOLOGY

4.1 Introduction

This chapter elaborates on the methods and equipment that were utilised to determine the level of major and trace elements in soil and road dust in order to assess their possible health risks. According to Mvuyane (2018), methodology refers to actions followed to study a research problem and the motivation for the utilisation of a particular method in identifying, selecting, processing and analysing data with the aim of comprehending the problem. Therefore, the methodology undertaken to investigate a research problem in this study included aspects such as sampling site and technique, sampling period and frequency, analytical methods, statistical analysis, pollution assessment methods, and risk assessment method. A summary of the procedures and stages is presented in Figure 4.1.

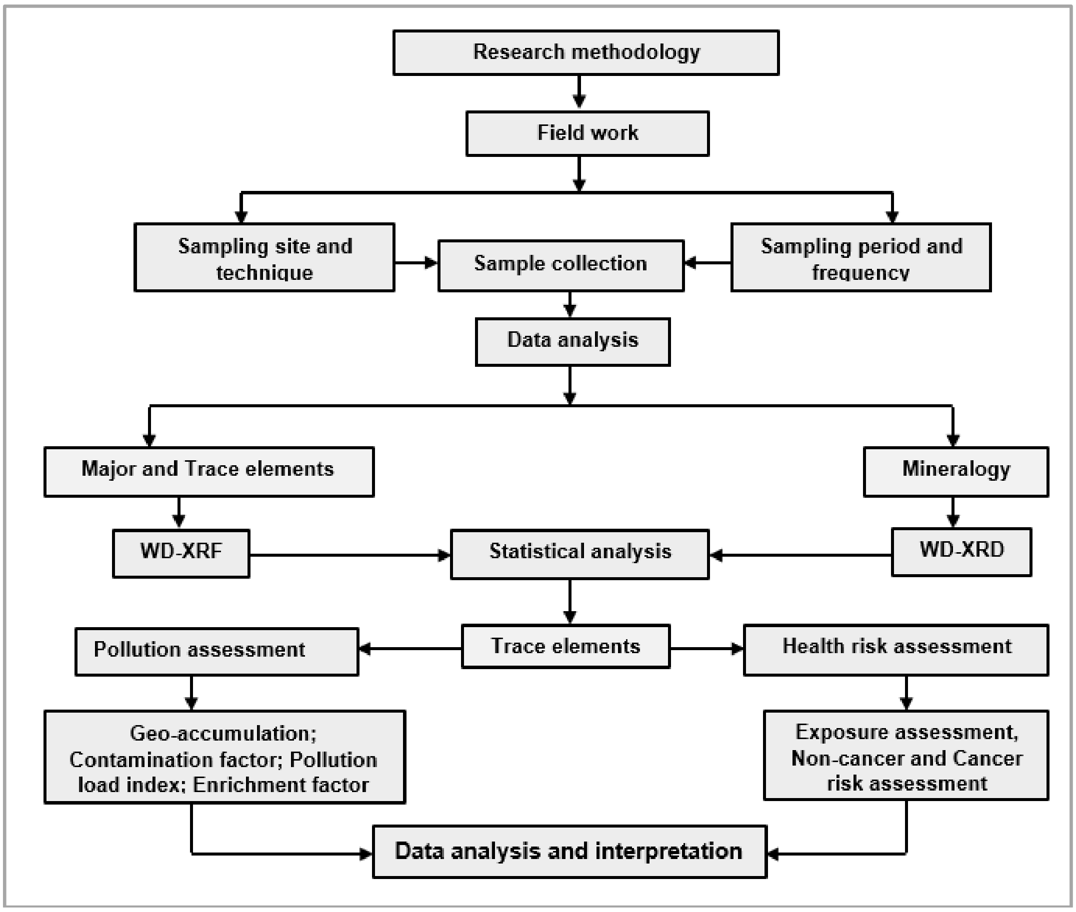

Figure 4.1 Materials and methods flow chart

4.2 Sampling site and technique

There are different functional areas within Winnie Mandela informal settlement. These include commercial and residential areas, roadways, taxi ranks and leisure parks/ playing grounds. All these functional areas were considered as sampling sites. These sites were selected because of public health concerns, as they are always used by local inhabitants, and found to be polluted most of the time. According to Bris et al. (1999), road dust can be collected by various techniques such as sweeping with a brush and dustpan, small vacuum sweeper trucks or by a battery-powered vacuum cleaner. In this study, sweeping with brush and dustpan was adopted to collect road dust samples as it is a convenient, simple (Bris et al. 1999) and frequently used technique (Ferreira-Baptista and De Miguel 2005; Othman et al. 2019; Tian et al. 2019) (Figure 4.2a). A sampling point was randomly chosen and dust particles, which had accumulated on paved road surfaces within a 5 m range around the chosen sampling point, were collected (Ferreira-Baptista and De Miguel 2005).

(a) (b)

Figure 4.2 Collection of (a) road dust and (b) soil samples (Author's own 2021)

Furthermore, soil sampling was done by the means of a stainless steel spade, clean bucket, plastic scoop and a ruler for depth measurement. The samples were taken at a depth of 0–20 cm at each sampling site (Figure 4.2b). Unrelated material, such as litter and debris, were removed from the samples in the course of sampling. The equipment were cleaned after every location to avoid cross-contamination. The collected samples were transferred into plastic sample bags. The samples were given an identity number (SL for soil samples and RD for road dust samples) for conveyance to the laboratory. A randomly selected sampling point within each unit was recorded and defined as presented in Table 4.1 and Figure 4.3.

Table 4.1 Location and characteristics of sampling point (Author's own compilation 2021)

Sample ID*	Description	GPS Coordinates	
		Latitude	**Longitude**
SL01	At the community leisure park	25°58'38.0"S	28°12'44.3"E
SL02	Adjacent to the community library	25°58'54.0"S	28°13'30.1"E
SL03	Adjacent to the shopping mall	25°58'35.5"S	28°13'43.8"E
SL04	At the community playground or soccer ground	25°58'44.5"S	28°13'50.7"E
SL05	Adjacent to the major road called Madiba Drive	25°58'26.7"S	28°13'26.1"E
RD01	At Madiba Drive next to the hardware store	25°58'22.1"S	28°13'27.1"E
RD02	At the southward drive, opposite the fuel station	25°58'00.3"S	28°12'57.6"E
RD03	At the community taxi rank	25°58'51.4"S	28°13'22.1"E
RD04	Next to primary school	25°58'50.7"S	28°13'30.1"E
RD05	Within the community shopping mall	25°58'33.0"S	28°13'42.2"E

*SL=Soil samples; RD=Road dust samples

Central University of Technology, Free State

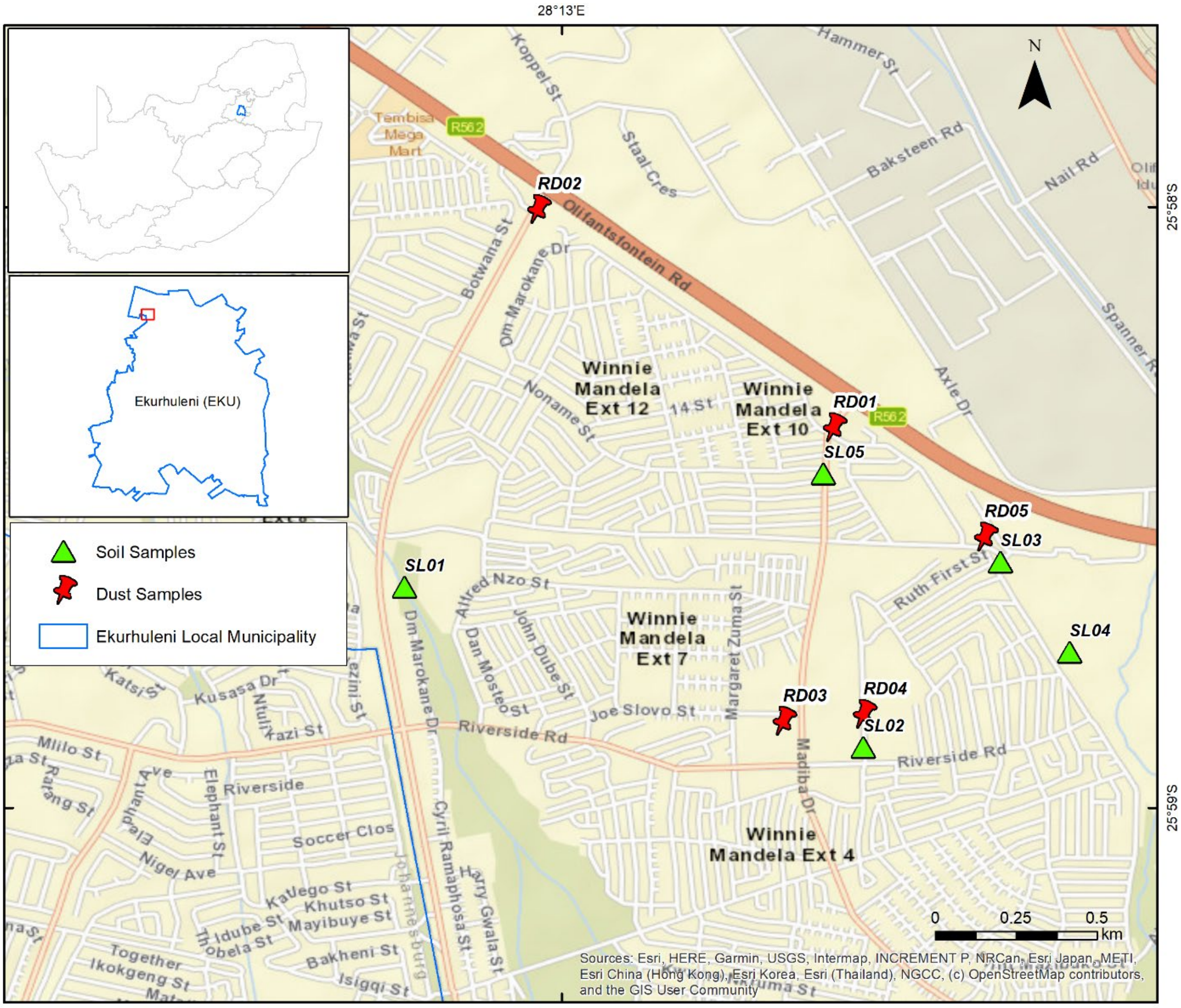

Figure 4.3 Soil and road dust sampling locations in Winnie Mandela informal settlement, South Africa

4.3 Sampling period and frequency

The sampling campaign was conducted in June 2021, which is a dry month. This was done to evade rain washing away road dusts. During the campaign, five (5) soil and five (5) road dust samples were collected randomly in different places within the settlement. Sample mass collected was approximately 350 g and 500 g for each sampling site (Figure 4.4). All the samples were collected during the day.

Figure 4.4 Collected soil and road dust samples (Author's own, 2021)

4.4 Data analysis

4.4.1 Wavelength Dispersive X-ray Fluorescence method

The Wavelength Dispersive X-ray Fluorescence (WD-XRF) method was used to analyse the major and trace elements in soil and road dust of Winnie Mandela informal settlement. XRF is a nondestructive method for analysis of elements. The fundamentals of XRF is based on various energies released by the atoms of a particular sample as a result of excitation by X-rays. This permit most of the elements in a particular sample to be analysed in a qualitative and quantitative manner. First, an atom is freed from the inner shell by X-rays and then the inner shell (K or L) is filled by the atom from an outside shell. As the energised atom returns to the unexcited level it emits energy in the X-ray area of the wavelength. The energised emitted photons are comparable to the variance among distinct shells. For example, the movement from the L-shell to the K-shell produces a spectral line known as $K\alpha$, whereas the movement from the M-shell to the K-shell produces a spectral line known as $K\beta$. Consequently, the respective element retains unique specific lines in the spectrum since every kind of orbital movement releases a different X-ray. Fluorescence energy is emitted by some energised atom when they yield to ground state and as a result, released photons are then identified. Elements that are in the sample are recognised by their energy peak position alongside the horizontal line (Sereyrath 2013).

Sample preparation and analysis

The samples were initially air-dried and then pulverised in an iron mill. The pulverised samples were partitioned by a quartering method. The sample was crushed once more into fine particles to produce a satisfactory amount of particles of every portion of the various material. A 60 µm sieve was used to sift the material and the large material retained were crushed once more until no particles larger than 60 µm were retained. A small sample with approximately 5% similarities was then taken for analysis, according to the sampling guideline of the International Atomic Energy Agency (1997). All the major elements were analysed on a fused bead. Sodium oxide (Na_2O) was run on a pressed pellet, whereas loss on ignition was determined by heating the sample to 1 050 °C. Furthermore, a pressed pellet was made using Hoechst wax for analysing the trace elements. In this study, the WD-XRF machine used was a Rigaku-Primus IV, with an Rh tube. The software for this machine was ZXS, which provides quantitative results.

4.4.2 X-ray diffraction method

An X-ray diffraction (XRD) method was utilised in the mineralogical analysis of soil and road dust. The method of X-ray diffraction depends on the ratio of X-rays elastically dispersed by electrons. The deflection episode is envisaged as a result of the contact among electromagnetic radiation and electrons. The electromagnetic radiation reaches the sample with a specific frequency and the electrons within the sample move with the waves, wavering in the path of the polarisation of the incident light. The moving electron then generates electromagnetic radiation which makes the wavering electrons in the sample to produce light in circular movements, together with the rate of the wavering electrons. As the number of incident X-rays diminishes, the energy is then transferred from the incident light into the wavering of the electrons. For X-rays to be deflected, they need to come in contact with the material displaying a periodicity in the delivery of electrons equivalent to the X-ray wavelength (λ). X-rays are distributed by electrons, and as a result, the distribution power of an atom is linked to its number of electrons (Lavina et al. 2014).

Sample preparation and analysis

Each sample was milled using an iron mill. Fine particles of less than 200 mesh in size were preferred. It was then placed into a sample holder which was then spread evenly onto a glass slide creating a level upper surface. It was then placed in a sample vessel and sprinkled onto a dual adhesive tape. Care was taken when making an even upper surface and to obtain unsystematic spreading of lattice orientations, to avoid forming orientated spread. Then a solid sample with a polished surface, thin films and liquid was measured directly by using the XRD method. In this study, the XRD analysis was completed using a PANalytical Empirical with a Cu-anode X-ray tube. For interpretation, a sleeve with the International Centre for Diffraction Data (ICDD) PDF−2 was used. The results are semi-quantitative.

4.5 Statistical data analysis

According to Mvuyane (2018), data analysis is the practice of ensuring that data is meaningful. Analysis of data involves breaking down data into representative components with the aim of answering the research questions (Strydom et al. 2002). The results from the laboratory analysis were sorted and arranged. It was then analysed by using the Statistical Package for Social Sciences (SPSS) in Microsoft Excel. The data are presented in figures and tables as minimum, maximum, mean and standard deviation. Furthermore, to determine the interrelationship and difference of various elements in the samples, Pearson correlation coefficients and one-way analysis of variance (ANOVA) were performed, respectively.

4.5.1 Pearson correlation coefficient analysis

This analysis was selected to analyse the elemental relationship strength. This helped to know if the elements are generated by the same source (Sebaiwa 2016). In the Pearson correlation coefficient analysis, the number between −1 and +1 is regarded as the correlation coefficient. Generally, it connotes that two variables change similarly on an average. Two variables are considered to have a positive correlation when they increase at the same time and the correlation coefficient is expected to be near +1. Furthermore, when one variable decreases while the other one increases, the correlation coefficient will be near −1 and is then considered to have a negative correlation (Sebaiwa 2016). The Pearson correlation coefficient analysis is based on several degrees which are presented in Table 4.2:

Table 4.2 Degree of correlation (r) (Sebaiwa 2016)

Value of r	Degree of correlation
± 1	Perfect correlation
± 0.90 or more	Very high degree of correlation
± 0.75 to ± 0.90	Sufficiently high degree of correlation
± 0.60 to ± 0.75	Moderate degree of correlation
± 0.30 to ± 0.60	Only the possibility of correlation
Less than ± 0.30	Possibly no correlation
0	Absence of correlation

4.5.2 One-way Analysis of Variance test

ANOVA is a technique used to test the null hypothesis that there is no difference between two or more variables (Sebaiwa 2016). The correlation coefficient is regarded as statistically significant when the probability (P-value) is below 5%, that is $P < 0.05$ (Sebaiwa 2016). It is referred as of no significant difference when the probability (P-value) is greater than 5%, that is $P > 0.05$. The ANOVA test was performed to establish the significant difference among the mean concentrations of heavy metals in soil and road dust samples.

4.6 Pollution level assessment and source identification of trace elements in soil and road dust

To assess the degree and sources of heavy metal pollution in soil and road dust samples, various pollution assessment methods or pollution indices were adopted (Othman et al. 2019). Pollution indices play a crucial role in effective evaluation of soil pollution with heavy metals (Kowalska et al. 2018). In this study, the geo-accumulation index (Igeo), contamination factor (CF), pollution load index (PLI) and enrichment factor (EF) were employed to assess the level and sources of heavy metal pollution in both soil and road dust samples.

4.6.1 Geo-accumulation index

Igeo was utilised in this study to evaluate the heavy metal pollution levels (Kowalska et al. 2018; Muller 1969; Oke and Vermeulen 2016; Timothy and Williams 2019). In this study, it was used to determine contamination assessment by matching the concentration of analysed elements to the average shale values (Ma and Singhirunnusorn 2012). It was computed by using Equation 1:

$$Igeo = log_2 \left(\frac{Cn}{1.5\ Bn} \right) \quad (1)$$

where Cn signifies the measured concentration of the metal of interest and Bn represents the concentration of the measured element in average shale value. The number 1.5 is the constant which is presented to reduce the effect of possible variations in the background values and can be attributed to the lithological differences in the sediments or soil (Ma and Singhirunnusorn 2012). Geo-accumulation values are useful in dividing soil into different quality classes or clusters and their classifications are described in Table 4.3 (Kowalska et al. 2018; Ma and Singhirunnusorn 2012; Muller 1969; Nowrouzi and Pourhabbaz 2014; Oke and Vermeulen 2016).

Table 4.3 Geo-accumulation index classifications (Kowalska et al. 2018)

Igeo value	Class	Soil quality
$Igeo \leq 0$	0	Uncontaminated
$0 < Igeo \leq 1$	1	Uncontaminated to moderately contaminated
$1 < Igeo \leq 2$	2	Moderately contaminated
$2 < Igeo \leq 3$	3	Moderately to heavily contaminated
$3 < Igeo \leq 4$	4	Heavily contaminated
$4 < Igeo \leq 5$	5	Heavily to extremely contaminated
$Igeo > 5$	6	Extremely contaminated

4.6.2 Contamination factor

CF was helpful in the assessment of the degree of soil pollution. It permits the evaluation of soil pollution by taking into consideration the content of heavy metals in the soil and pre-industrial reference levels or background values (Kowalska et al. 2018). CF was calculated by using Equation 2:

$$CF = \frac{Concentration\ sample}{Concentration\ background} \quad (2)$$

where the concentration sample represents the analysed metal concentrations and concentration background is the metal concentration in average shale value. The contamination factor values were categorised into four different clusters, CF < 1 indicates low contamination; 1 ≤ CF < 3 indicates moderate contamination; 3 ≤ CF ≤ 6 describes considerable contamination; and CF > 6 describes very high contamination (Addo et al. 2012; Mmolawa 2011).

4.6.3 Pollution load index

PLI was used to assess the degree of contamination in both soil and road dust. It provides a simple procedure to verify how environmental conditions has deteriorated due to the increase of heavy metals (Kowalska et al. 2018; Taofeek and Tolulope 2012; Varol 2011). PLI was computed by using Equation 3:

$$PLI = \sqrt[n]{CF1 \times CF2 \times CF3 \times \ldots Cfn} \quad (3)$$

where *n* represents the number of metals analysed and CF connotes the contamination factor computed by Equation 2. PLI offers an important way to assess the quality of the site as described in Table 4.4.

Table 4.4 Pollution load index values (Kowalska et al. 2018)

Pollution load index (PLI) values	Category
0 < PLI ≤ 1	Unpolluted
1 < PLI ≤ 2	Moderately to unpolluted
2 < PLI ≤ 3	Moderately polluted
3 < PLI ≤ 4	Moderately to highly polluted
4 < PLI ≤ 5	Highly polluted
5 < PLI	Very highly polluted

4.6.4 Enrichment factors

EF is a scientific method used to assess the level of trace element pollutions (Ghanavati et al. 2019; Liu et al. 2014; Yuen et al. 2012). It distinguishes heavy metal concentrations originating from human origin to those originating from natural sources (Sebaiwa 2016). The enrichment factor assessment of various trace elements was computed by comparing the concentration of an element in a sample with its concentration in the average shale value. Elements such as aluminium (Al), zirconium (Zr), titanium (Ti), iron (Fe) or scandium (Sc) may be utilised as background or reference material (Sebaiwa 2016). The current study adopted Sc as the background or reference material (Ghavanati et al. 2019). The EF was computed by means of Equation 4:

$$EF = \frac{\left(\frac{E}{R}\right)sample}{\left(\frac{E}{R}\right)background} \tag{4}$$

where E is the elemental concentration, R is a reference element (Sc) of crustal material and the E/R sample is the concentration ratio of E to R in the collected samples and E/R background is the concentration ratio of E to R in the earth's crust. As reported by Ghavanati et al. (2019), EF values of $0.05 \leq EF \leq 1.5$ is an indication that the toxic metal originated completely from crustal materials or a natural source, whereas values greater than 1.5 show an anthropogenic source of toxic metals. The degree of pollution was categorised in five classes as described in Table 4.5 (Ghavanati et al. 2019; Sebaiwa 2016).

Table 4.5 Enrichment categories of enrichment factor values (Ghavanati et al. 2019)

Enrichment factor value	Category
EF < 2	Depletion to minimal enrichment
EF = 2–5	Moderate enrichment
EF = 5–20	Significant enrichment
EF = 20–40	Very high enrichment
EF > 40	Extremely high enrichment

4.7 Health risk assessment of trace elements in soil and road dust

The health risk assessment model was used to assess the health risks associated with trace elements exposure in soil and road dusts from Winnie Mandela informal settlement for both children and adults. Exposure pathways to heavy metals may occur through ingestion, inhalation, and dermal contact (Qadeer et al. 2020). Noncarcinogenic and carcinogenic risk of trace elements in soil and road dust through these exposure pathways were assessed.

4.7.1 Noncarcinogenic risk assessment

To assess the noncarcinogenic risks, the average daily dose (ADD) of each heavy metal obtained through ingestion, inhalation and dermal contact, was calculated (Gabarrón et al. 2017). It was computed with the use of Equations 5, 6 and 7 (Gabarrón et al. 2017; Qadeer et al. 2020; USEPA 1996).

$$ADD_{ing} = \frac{C \times IngR \times CF \times EF \times ED}{BW \times AT} \quad (5)$$

$$ADD_{inh} = \frac{C \times InhR \times EF \times ED}{BW \times AT \times PEF} \quad (6)$$

$$ADD_{derm} = \frac{C \times SA \times CF \times SL \times ABS \times EF \times ED}{BW \times AT} \quad (7)$$

where ADD_{ing} signifies the average daily ingestion (mg/kg/day) exposure amount of an element; ADD_{inh} indicates the average daily inhalation (mg/kg/day) exposure amount of an element; and ADD_{derm} specifies the average daily dermal (mg/kg/day) exposure amount of metal. The values of these factors are presented in Table 4.6.

Noncarcinogenic risk was then evaluated from the hazard quotient (HQ) for every trace element. It was computed by dividing the ADD calculated in Equations 5, 6 and 7 by a particular reference dose (Rfd) using Equation 8:

$$HQ = \frac{ADD}{RfD} \quad (8)$$

where ADD was less than the RfD, it signified no possibility of health effects. HQ values higher than one, suggested a possibility of health effects, while HQ values of less than one, was a sign for no possibility of health effects (Chonokhuu et al. 2019). The hazard index (HI) was then calculated by adding the hazard quotients of the three various forms of exposure pathways for a corresponding element (Zgłobicki et al. 2021). It was computed by using Equation 9:

$$HI = (HQ)_{ing} + (HQ)_{inh} + (HQ)_{derm} \tag{9}$$

HI value < 1 described a very low risk; an HI value of between 1 and 4 showed that a risk effect was possible, and HI value > 4 described a high risk (Zgłobicki et al. 2021).

4.7.2 Carcinogenic risk assessment

The lifetime average daily dose (LADD) of each analysed element was also calculated for all three potential pathways of exposure (ingestion, inhalation and dermal) using Equations 10 to 12 (Ferreira-Baptista and De Miguel 2005; Qadeer et al. 2020; USEPA 1996, 2002).

$$LADD_{ing} = \frac{C \times CF \times EF}{AT} \times \left(\frac{IngR_{child} \times ED_{child}}{BW_{child}} + \frac{IngR_{adult} \times ED_{adult}}{BW_{adult}}\right) \tag{10}$$

$$LADD_{inh} = \frac{C \times EF}{AT \times PEF} \times \left(\frac{InhR_{child} \times ED_{child}}{BW_{child}} + \frac{InhR_{adult} \times ED_{adult}}{BW_{adult}}\right) \tag{11}$$

$$LADD_{derm} = \frac{C \times CF \times EF \times SL \times ABS}{AT} \times \left(\frac{SA_{child} \times ED_{child}}{BW_{child}} + \frac{SA_{adult} \times ED_{adult}}{BW_{adult}}\right) \tag{12}$$

where, $LADD_{ing}$ connotes the lifetime average daily ingestion (mg/kg/day) exposure amount of a metal; $LADD_{inh}$ implies the lifetime average daily inhalation (mg/kg/day) exposure amount of an element; and $LADD_{derm}$ indicates the lifetime average daily dermal (mg/kg/day) exposure amount of a metal. Table 4.6 summarises the aspects of exposure for the above models (Ferreira-Baptista and De Miguel 2005; Gabarrón et al. 2017; Li et al. 2013; Lu et al. 2014; Qadeer et al. 2020; USEPA 2002).

After calculating the LADD of each exposure pathway, a lifetime carcinogenic risk (LCR) was then computed by multiplying the LADD with an equivalent slope factor (SF).

$$LCR = LADD \times SF \tag{13}$$

The permissible risk usually range from 10^{-6} to 10^{-4} (Han 2017; Lu et al. 2014; Rendell and McGinty 2007; USEPA 1991; Yalala 2015) and were interpreted with the help of the values presented in Table 4.7.

Table 4.6 Exposure factors for dose models (Qadeer et al. 2020)

Items	Parameter	Meaning	Unit	Value	
				Children	**Adults**
Basic parameter	C	Concentration of a metal	mg/kg	This study	This study
	D	Daily dose	mg/kg		
	CF	Conversion factor	kg/mg	1×10^{-6}	1×10^{-6}
Exposure behavioural parameter	ED	Exposure duration	years	6	24
	BW	Body weight	kg	15	55.9
	EF	Exposure frequency	days/year	350	350
	AT	Average time (carcinogen)	days	365 × 70	365 × 70
		Average time (noncarcinogen)	days	365 × ED	365 × ED
Digestive tract/ inhalation	InhR	Inhalation rate	m^3/kg	5	20
	IngR	Ingestion rate	mg/kg	200	100
	PEF	Particle emission factor	m^3/kg	1.32×10^9	1.32×10^9
Skin contact	SL	Skin adherence factor	mg/cm^2	1	1
	SA	Skin surface area	cm^2	1 800	5 000
	ABS	Dermal absorption	–	0.001	0.001

Table 4.7 Interpretation of the risk numbers (Yalala 2015)

Risk	Risk in exponential	Risk in decimal	Read as a risk of element
1.0E-8	1×10^{-8}	0.00000001	1 in 100 million
1.0E-7	1×10^{-7}	0.0000001	1 in 10 million
1.0E-6	1×10^{-6}	0.000001	1 in 1 million
1.0E-5	1×10^{-5}	0.00001	1 in 100 000
1.0E-4	1×10^{-4}	0.0001	1 in 10 000
1.0E-3	1×10^{-3}	0.001	1 in 1000
1.0E-2	1×10^{-2}	0.01	1 in 100
1.0E-1	1×10^{-1}	0.1	1 in 10

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CHAPTER 5
RESULTS AND DISCUSSIONS

5.1 Introduction

This section presents the findings and discussions of the mineralogy, the concentration of major and trace elements, pollution level and sources of trace elements in soil and road dust. The mean concentration of trace elements in both soil and road dust was used to assess noncarcinogenic and carcinogenic risks. Furthermore, health implications related to heavy metal exposures are also discussed.

5.2 Mineralogy and concentration of major elements in soil and road dust

The mineralogical composition of soil and road dust was attained by the use of the X-ray diffraction (XRD) method and its descriptive statistics are presented in Table 5.1.

Table 5.1 Mineralogical characteristics of soil and road dust samples from Winnie Mandela informal settlement

Elements	Mineralogical composition of soil (Wt. %)					Mineralogical composition of road dust (Wt. %)			
	*N	Min	Max	Mean	±SD	Min	Max	Mean	±SD
Calcite	5	2.0	2.0	2.0	0.0	2.0	3.0	2.25	0.5
Clinochlore	5	–	–	–	–	8.0	8.0	8.0	0.0
Cordierite	5	11.0	11.0	11.0	0.0	7.0	7.0	7.0	0.0
Dolomite	5	3.0	4.0	3.5	0.7	3.0	8.0	4.6	1.9
Hematite	5	7.0	8.0	7.4	0.5	–	–	–	–
K-feldspar/rutile	5	6.0	9.0	8.0	1.2	5.0	10.0	7.6	1.8
Mica	5	12.0	15.0	13	1.2	9.0	13.0	9.8	1.8
Plagioclase	5	8.0	10.0	8.4	0.9	6.0	9.0	6.8	1.3
Pyrite	5	–	–	–	–	4.0	4.0	4.0	0.0
Quartz	5	39.0	52.0	47.0	5.4	48.0	65.0	59.6	7.2
Serpentine	5	11.0	13.0	12.2	0.8	6.0	9.0	7.5	1.3

Note: N=number of samples; Min=Minimum; Max=Maximum; SD=Standard deviation.

The mineralogical analysis of soil revealed different types of minerals, and its concentration raged from quartz (39–47%), plagioclase (8–10%), calcite (2–2%), K-feldspar/rutile (6–9%), dolomite (3–4%), mica (12–15%), serpentine (11–13%), cordierite (11–11%) and hematite (7–8%). The mean concentrations were 47%, 8.4%, 2%, 8%, 3.5%, 13%, 12.2%, 11% and 7.4%, respectively. Clinochlore and pyrite were below the detection limits.

In road dust, the concentrations of minerals ranged between quartz (48 and 65%), mica (9 and 13%), clinochlore (8 and 8%), K-feldspar/rutile (5 and 10%), serpentine (6 and 9%), cordierite (7 and 7%), plagioclase (6 and 9%), dolomite (3 and 8%), pyrite (4 and 4%) and calcite (2 and 3%), with mean concentrations of 59.6%, 9.8%, 8%, 7.6%, 7.5%, 7%, 6.8%, 4.6%, 4% and 2.25%, respectively. Only hematite was below the detection limit.

The mineralogical compositions of soil in Winnie Mandela informal settlement were descending as quartz, mica, serpentine, cordierite, plagioclase, K-feldspar/rutile, hematite, dolomite and calcite. Quartz was the dominant mineral followed by mica, whereas calcite was the least mineral. The concentrations of minerals in road dust in a decreasing order were quartz, mica, clinochlore, K-feldspar/rutile, serpentine, cordierite, plagioclase, dolomite, pyrite, calcite. Quartz was also the main mineral with the least amount of calcite. In comparison, quartz in road dust samples was higher than all the minerals within the study (Figure 5.1).

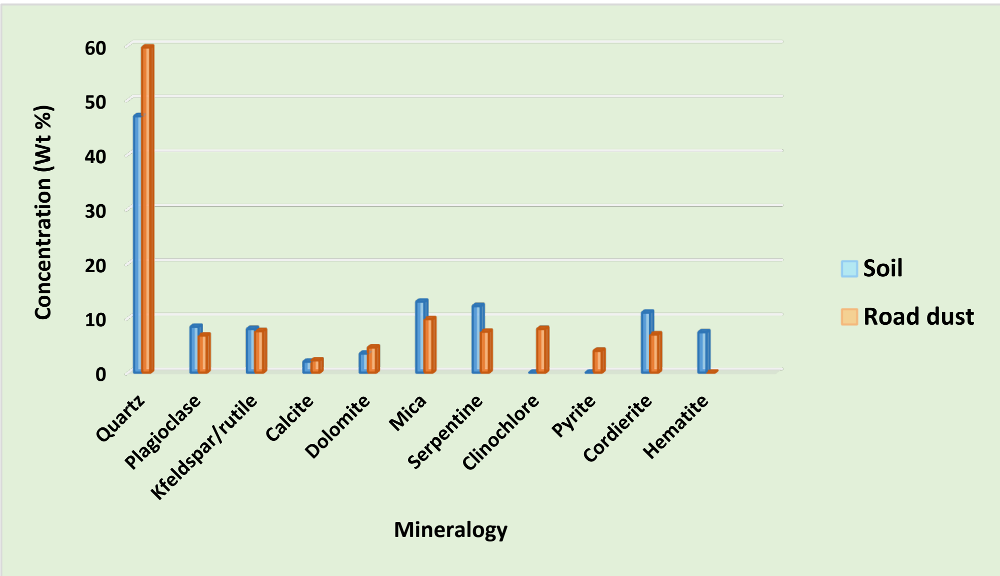

Figure 5.1 Mineralogical composition of soil and road dust from Winnie Mandela informal settlement

According to Gunawardana et al. (2012), soil and road dust in South East Queensland, Australia, were dominated by quartz, which is similar to the outcomes of this study. The findings of this study are comparable to those in Viana do Castelo City, Portugal (Candeias et al. 2020), which also observed minor amounts of calcite in road dust. The mineral composition of road dust were identical to those identified in soil samples. According to Xie et al. (2000), these outcomes suggest a contribution of the surrounding soil to that of the road dust. Furthermore, the dominance of quartz in both soil and road dust may also be linked to the geographical location of the study area that falls under the Johannesburg Dome, underlain by sedimentary rocks of the Witwatersrand and Ventersdorp Supergroup (RoadLab 2014).

The descriptive statistics of the major elements in soil and road dust that were analysed by the Wavelength Dispersive XRF (WD-XRF) method are summarised in Table 5.2 with average shale values (ASV). The minimum and maximum concentrations of major elements in soil samples were as SiO_2 (55.9 to 70.6%), TiO_2 (0.7 to 1.0%), Al_2O_3 (9.3 to 11.7%), Fe_2O_3 (7.0 to 8.1%), MgO (0.1 to 0.4%), MnO (0.6 to 2.3%), CaO (0.4 to 1.0%), Na_2O (0.1 to 0.4%), K_2O (0.6 to 1.6%) and P_2O_5 (0.1 to 0.2%). Their mean concentrations were 68%, 0.8%, 10.8%, 7.8%, 0.3%, 1.0%, 0.7%, 0.2%, 0.9% and 0.2%, respectively.

In road dust samples, the minimum and maximum concentrations ranged from SiO_2 (65.37 to 79.92%), TiO_2 (0.35 to 0.48%), Al_2O_3 (3.41 to 4.67%), Fe_2O_3 (3.41 to 4.67%), MgO (0.32 to 1.33%), MnO (0.24 to 1.03%), CaO (1.09 to 4.23%), Na_2O (0.62 to 1.89%), K_2O (1.22 to 2.44%), and P_2O_5 (0.08 to 0.37%) with the mean concentrations of 72.76%, 0.40%, 6.90%, 3.88%, 0.94%, 0.57%, 2.71%, 0.99%, 1.56% and 0.16%, correspondingly.

Table 5.2 Composition of major elements in soil and road dust samples from Winnie Mandela informal settlement

Elements	Major elements in soil (Wt. %)					Major elements in road dust (Wt. %)				
	*N	Min	Max	Mean	±SD	Min	Max	Mean	±SD	ASV
Al_2O_3	5	9.3	11.7	10.8	1.0	5.9	8.43	6.9	0.99	15.4
CaO	5	0.4	1.0	0.7	0.2	1.09	4.23	2.71	1.26	3.1
Fe_2O_3	5	7.0	8.1	7.8	0.5	3.41	4.67	3.88	0.52	4.02
K_2O	5	0.6	1.6	0.9	0.4	1.22	2.44	1.56	0.5	3.24
MgO	5	0.1	0.4	0.3	0.1	0.32	1.33	0.94	0.41	2.44
MnO	5	0.6	2.3	1.0	0.7	0.24	1.03	0.57	0.3	trace
Na_2O	5	0.1	0.4	0.2	0.1	0.62	1.89	0.99	0.52	1.3
P_2O_5	5	0.1	0.2	0.2	0.0	0.08	0.37	0.16	0.12	0.14
SiO_2	5	65.9	70.6	68	1.7	65.37	79.92	72.76	5.62	58.11
TiO_2	5	0.7	1.0	0.8	0.1	0.35	0.48	0.4	0.06	0.65
LOI	5	6.7	8.42	7.5	0.8	4.98	11.3	8.18	2.67	-

Note: N=number of samples; SD=Standard deviation; ASV= Average shale value (Clarke and Washington 1924); Min=Minimum; Max=Maximum; LOI=Loss of ignition.

The principal oxide in soil samples was SiO_2 (68.0%). It was followed by aluminium oxide with 10.8% and iron oxide with 7.8% mean concentration (Figure 5.2). All other oxides were below 1.2%. The major elements in soil decreased with a huge difference as SiO_2 (68%), Al_2O_3 (10.8%), Fe_2O_3 (7.8%), MnO (1.0%), K_2O (0.9%), TiO_2, (0.8%), CaO (0.7%), MgO (0.3%), P_2O_5 (0.2%), Na_2O (0.2%). In urban soil of the Xi'an City in China, Li et al. (2019) also observed SiO_2 as a principal oxide. As shown in Figure 5.2, silica (72.76%) was also a dominant major element in road dust, followed by aluminium oxide (6.90%) and iron oxide (3.88%). P_2O_5 was the least major oxide in the road dust samples. Their mean concentrations were descending as SiO_2 (72.76%), Al_2O_3 (6.90%), Fe_2O_3 (3.88%), CaO (2.71%), K_2O (1.56%), Na_2O (0.99%), MgO (0.94%), MnO (0.57%), TiO_2 (0.40%) and P_2O_5 (0.16%). These results are comparable to those reported by Gunawardana et al. (2012) in road dust samples of South East Queensland, Australia, who also observed silica as a leading major oxide.

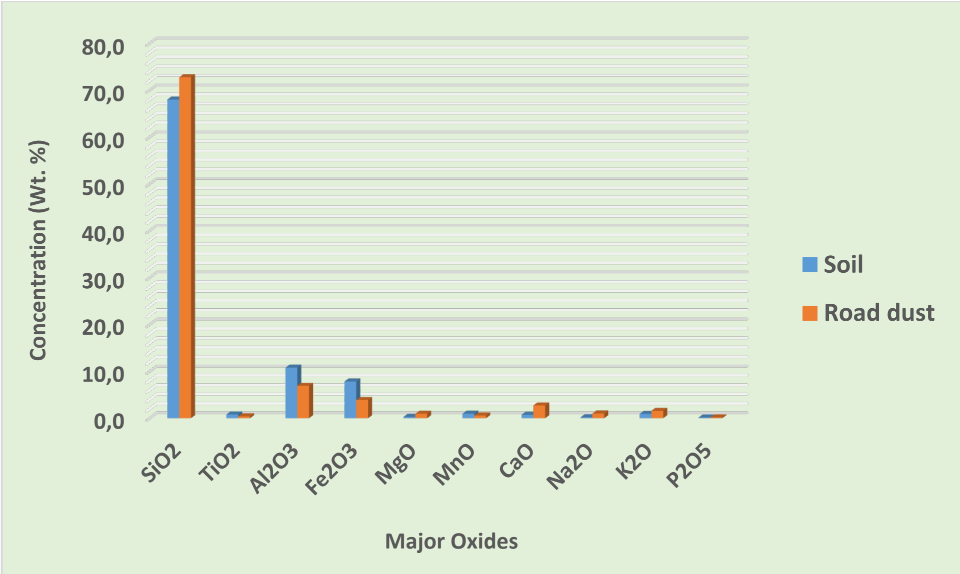

Figure 5.2 Major oxides in soil and road dust of Winnie Mandela informal settlement

When compared with the average shale values, major elements such as SiO_2, Fe_2O_3, P_2O_5 and TiO_2 were above their average shale values in soil samples. In road dust, only SiO_2 and P_2O_5 were higher than their average shale values (Figure 5.3). Similar reports of silica being higher than its reference values was reported by Gunawardana et al. (2012). These findings suggest that the community may be exposed to serious health implications due to exposure of high silica content.

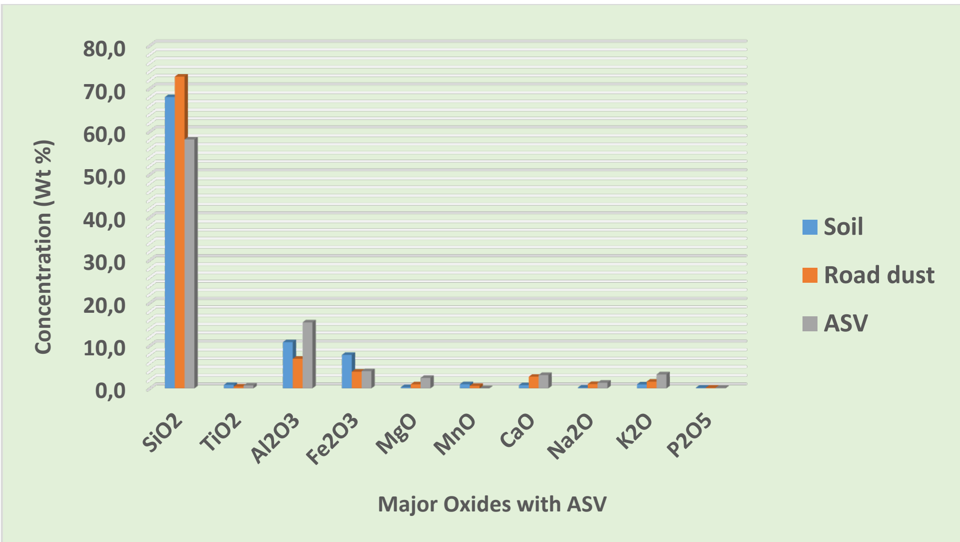

Figure 5.3 Comparison of major oxides in soil and road dust with average shale values

According to Sebaiwa (2016), exposure to high silica dust may cause microscopic damaging of lung tissue which may lead to development of a fibrous growth, loss of lung elasticity as well as a large reduction of gas exchange area. The dominance of silica in both soil and road dust can be attributed to the fact that quartz is a ubiquitous mineral and has higher structural hardness than other minerals, which prevent its physical weathering (Candeias et al. 2020). Furthermore, the geology of the study area may also have influenced quartz abundance. According to Salah et al. (2013), variations in elemental concentrations can be attributed to different geologic conditions.

Furthermore, the results also showed TiO_2 to be higher than its average shale value in soil samples which may be linked to waste materials containing titanium oxides used as a pigment in white paint used for vehicles (Fujiwara et al. 2011). Exposure to high concentrations of TiO_2 is believed to result in medical conditions such as constriction of nuclear membranes, apoptosis, and altered cell cycles (Baranowska-Wojcik et al. 2019). The concentration of Fe_2O_3, which was higher than its average shale value, was similar to those results obtained in soil of Xi'an, China (Li et al. 2019). Corrosion of vehicles metal parts may have contributed to high concentrations of Fe_2O_3 in soil of Winnie Mandela informal settlement (Pozhitkov and Ukarkhanova 2021). Exposure to high concentrations of Fe_2O_3 may result in lung fibrosis, siderosis and silicosis (Lewinski et al. 2013). Additionally, the concentration of P_2O_5 was also higher than its average shale value in both soil and road dust, which is in agreement with a study conducted by Pozhitkov and Ukarkhanova (2021). According to Candeias et al. (2020), the use of phosphate in different agricultural activities may exacerbate the concentration of P_2O_5, which may have been influenced by poor waste management practices in this informal settlement. The community may be at risk of respiratory distress, and liver, kidneys and brain problems as a result of exposure to high concentrations of P_2O_5 (USEPA 1990). Furthermore, the mean concentration of major elements such as Al_2O_3, K_2O, MgO, MnO, and CaO were below their average shale values in both soil and road dust samples, suggesting that they are of natural origin and are comparable to the findings of Li et al. (2019) in Xi'an city, China.

5.3 Concentration of trace elements in soil and road dust

The concentration of trace elements in soil and road dust were analysed by a WD-XRF method. The minimum, maximum, mean and standard deviation (± SD) concentrations of trace elements such as As, Ba, Co, Cr, Cu, Nb, Ni, Pb, Rb, Sc, Sr, Th, U, V, Y, Zn, and Zr in five (5) soil and five (5) road dust samples of Winnie Mandela informal settlement are presented in Table 5.3, together with their average shale values (ASV).

Table 5.3 Statistical analysis of trace element concentration in soil and road dust samples from Winnie Mandela informal settlement with average shale values

Elements	Trace element concentrations in soil samples (mg/kg)					Trace element concentrations in road dust (mg/kg)				
	*N	Min	Max	Mean	±SD	Min	Max	Mean	±SD	ASV
As	5	10	42	18.8	13.4	4	10	7.2	2.9	13
Ba	5	450	704	573.2	104.2	546	729	625.6	73.9	580
Co	5	38	54	46.8	7.1	15	20	17.4	2.1	19
Cr	5	452	2361	1070	773.2	283	1088	637.4	297	90
Cu	5	58	134	85.8	29.9	42	125	61	35.9	45
Nb	5	12	15	12.8	1.3	8	9	8.6	0.5	11
Ni	5	59	142	86	32.6	32	80	49	19	68
Pb	5	9	70	25.8	25.1	17	41	30.8	8.8	20
Rb	5	52	97	66.6	17.9	56	82	66	10.8	140
Sc	5	11	16	13	1.9	4	8	5.8	1.6	13
Sr	5	41	86	62.2	19.4	81	156	120.2	33.2	300
Th	5	2.9	10	7.38	2.9	2.9	6	4.58	1.5	12
U	5	2.9	4	3.18	0.5	2.9	2.9	2.9	0.0	3.7
V	5	149	191	178.8	17.1	55	82	69	12.2	130
Y	5	11	22	17.4	4.4	14	15	14.4	0.5	26
Zn	5	66	151	104.2	31	67	700	231.8	263.4	95
Zr	5	224	265	237.6	16.5	164	227	190.2	31.1	160

Note: N=number of samples; SD=Standard deviation; ASV= Average shale value (Turekian and Wedepohl 1961); Min=Minimum; Max=Maximum.

The minimum and maximum concentrations of trace elements in soil were Sc (11 to 16), V (149 to 191), Cr (452 to 2361), Co (38 to 54), Ni (59 to 142), Cu (58 to 134), Zn (66 to 151), As (10 to 42), Rb (52 to 97), Sr (41 to 86), Y (11 to 22), Zr (224 to 265), Nb (12 to 15), Ba (450 to 704), Pb (9 to 70), Th (2.9 to 10) and U (2.9 to 4) mg/kg. Their corresponding mean and ± SD concentrations were (13 ± 1.9), (178.8 ± 17.1), (1070 ± 773.2), (46.8 ± 7.1), (86 ± 32.6), (85.8 ± 29.9), (104.2 ± 31.0), (18.8 ± 13.4), (66.6 ± 17.9), (62.2 ± 19.4), (17.4 ± 4.4), (237.6 ± 16.5), (12.8 ± 1.3), (573.2 ± 104.2), (25.8 ± 25.1), (7.38 ± 2.9) and (3.18 ± 0.5) mg/kg.

In road dust, the concentration of trace elements ranged from Sc (4 to 8), V (55 to 82), Cr (283 to 1088), Co (15 to 20), Ni (32 to 80), Cu (42 to 125), Zn (67 to 700), As (4 to 10), Rb (56 to 82), Sr (81 to 156), Y (14 to 15), Zr (164 to 227), Nb (8 to 9), Ba (546 to 729), Pb (17 to 41), Th (2.9 to 6) and U (2.9 to 2.9) mg/kg with mean and ± SD concentrations of (5.8 ± 1.6), (69 ± 12.2), (637.4 ± 297.0), (17.4 ± 2.1), (49 ± 19.0), (61 ± 35.9), (231.8 ± 263.4), (7.2 ± 2.9), (66 ± 10.8), (120.2 ± 33.2), (14.4 ± 0.5), (190.2 ± 31.1), (8.6 ± 0.5), (625.6 ± 73.9), (30.8 ± 8.8), (4.58 ± 1.5) and (2.9 ± 0.0) mg/kg, respectively.

The comparison of the mean concentrations of the trace elements in soil and road dust from Winnie Mandela informal settlement showed considerably differences (Figure 5.4). The descending trends of the mean concentrations of the trace elements were as follows: Cr > Ba > Zr > V > Zn > Ni > Cu > Rb > Sr > Co > Pb > As > Y > Sc > Nb > Th > U and Cr > Ba > Zn > Zr > Sr > V > Rb > Cu > Ni > Pb > Co > Y > Nb > A > S > Th > U in soil and road dust, respectively. The mean concentration of Cr in soil was above all the trace elements, whereas U had the lowest mean concentration. In the road dust sample, Cr and U recorded the highest and lowest mean concentrations, respectively. The high concentration of Cr in both soil and road dust indicates contribution of anthropogenic activities, possibly from waste with fertiliser impurities, combustion of lubricants and fuel (Moryani et al. 2020). Ba was ranked second highest in both soil and road dust which may be possibly attributed to human activities such as waste from paint, ceramics, glass, plastics and traffic activities such as tires and wearing of brake pads (Sager 2020), whereas the value of U suggests that it is of natural origin. With all the trace elements considered within this study, the results revealed that soil samples had the highest concentrations of trace elements as compared to the road dust samples, signifying possible health risks to the local inhabitants mainly from Cr which recorded a staggering high concentration.

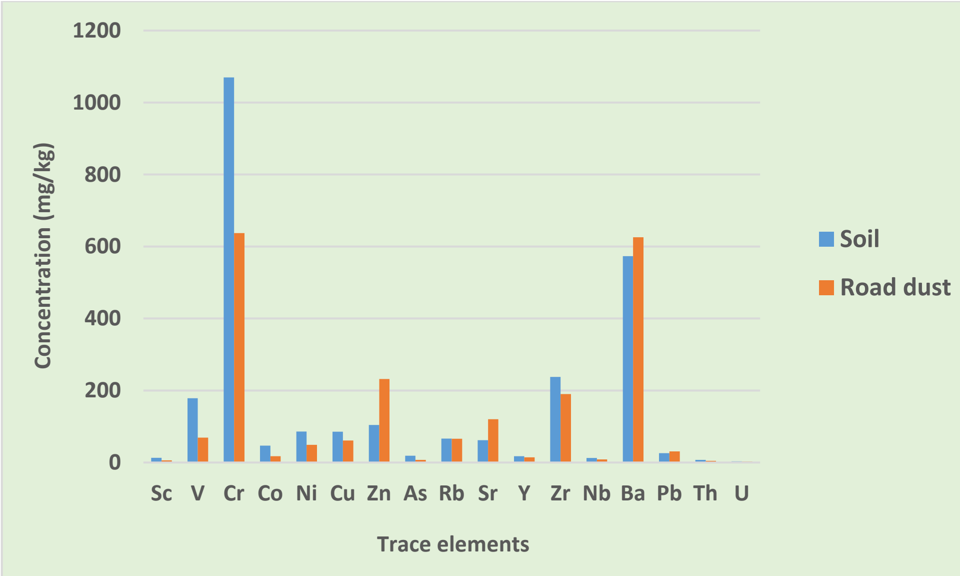

Figure 5.4 Concentration of trace elements soil and road dust of Winnie Mandela informal settlement

The extreme high concentration of Cr in soil and road dust may expose the population of Winnie Mandela informal settlement to serious health implications since Cr is a carcinogenic element (Victoria et al. 2014) and may also affect the surrounding environment. According to Ray (2016), exposure to high concentration of Cr may cause health implications such as asthma, chronic bronchitis, lungs and nasal cancers, disorder of liver cells, irritant and allergic contact dermatitis. High concentrations of Cr in the environment may reduce the roots of plants, affect the process of germination and even cause the death of plants (Okereafor et al. 2020). Furthermore, high levels of Ba may expose local communities to health implications such as renal failure, respiratory paralysis, pulmonary oedema, and intestinal haemorrhages (Kravchenko et al. 2014).

Moreover, in comparison with the average shale values (Figure 5.5), the mean values of Rb, Sr, Y, Ba, Th and U in soil were below their average shale values. Sc was the only element with the same mean value as its average shale value. In road dust, Sc, V, Co, Ni, As, Rb, Sr, Y, Nb, Th and U were below their average values. This finding signifies that trace elements such as Sc, V, Co, Ni, As, Rb, Sr, Y, Nb, Th, Ba and U in the soil and road dust were of natural origin. This is comparable to the findings by Khan et al. (2018) in street dust in Dhaka city, Bangladesh, who discovered As to be below its background value, and those obtained by Li et al. (2019) in street dust in Xi'an, China, who witnessed Y, Zr, Sr, Rb, Nb, Co and Ni to be below their background values. According to Maeaba et al. (2019), natural sources of heavy metals may include resuspended soil particles, precipitation, geological weathering or erosion.

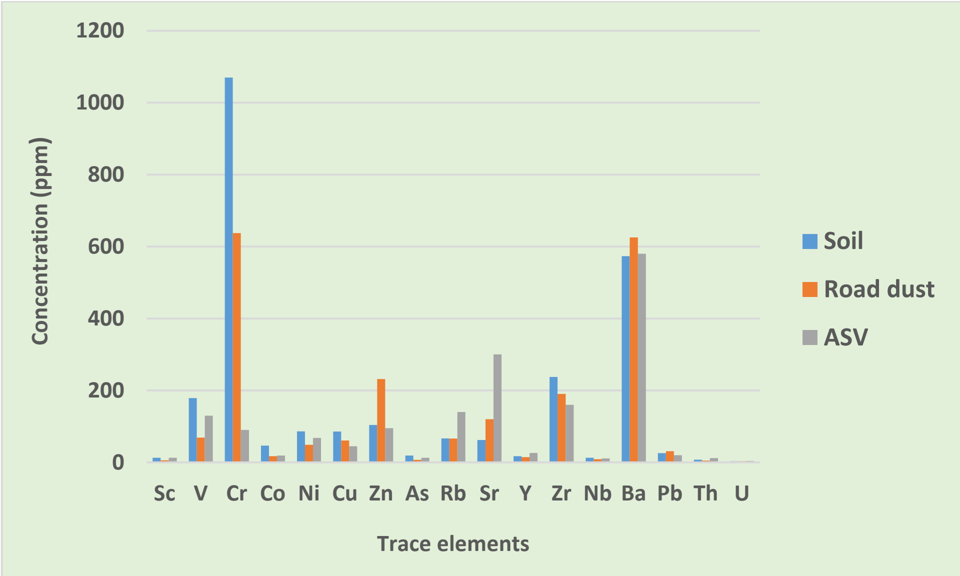

Figure 5.5 Comparison of trace elements in soil and road dust with average shale value

In addition, the findings of this study also revealed the mean concentration of V, Cr, Co, Ni, Cu, Zn, As, Zr, Nb and Pb in soil samples to be above their average shale values, which is identical to the outcomes of other researchers in urban soil of the Tuzla district, Istanbul (Sezgin et al. 2019), who observed Cu, Pb and Zn to be above the crustal mean values. This was also found in a study by Odat (2013) on soil along the Irbid–Zarqa highway in Jordan, who witnessed Co, Zn, Ni and Pb to be above their average shale values. In road dust, Cr, Cu, Zn, Zr, Ba and Pb were also above their average shale values, which is in agreement with the findings of Cai and Li (2019) in street dust of Shijiazhuang, China, which revealed high concentrations of Cr, Ni, Cu, Pb and Zn, and also the study by Li et al. (2019) in street dust of Xi'an, China, who affirmed Ba concentrations to be above its background value. These outcomes signified that the pollution of soil and road dust by trace elements such as V, Ba, Cr, Co, Ni, Cu, Zn, As, Zr, Nb and Pb were possibly associated with traffic and anthropogenic activities.

Considering that the study area is an informal settlement, then dense traffic and anthropogenic activities such as unplanned construction, high population, high waste generation, coal combustion, sewage waste, unregulated waste incineration and poor waste management practices may be considered as the main contributors to the high concentrations of trace elements such as V, Ba, Cr, Co, Ni, Cu, Zn, As, Zr, Nb and Pb. High road traffic on a daily basis within the study area may have contributed to high levels of Zr in soil and road dust. According to Chen et al. (2015), Zr is possibly emanated from vehicle exhaust fumes due to its use in catalysts as zirconia dioxide (ZrO_2). The high level of Zn in this area is probably associated with traffic volumes. Valotto et al. (2015) and Candeias et al. (2020) confirmed that tyre rubber, brake wear, resuspended particles and fuel combustion are the major contributors of Zn in an urban environment. Poor waste management in this informal settlement and dense traffic may be the possible contributor to the high Ba levels. As reported by Sager (2020), the possible sources of Ba are waste materials from paint, ceramics, glass or plastics, tyres and brakes.

Moreover, sewage wastes and traffic movements within the settlement had played a huge role in the rise of Cu, Pb, Ni and Cr in soil and road dust. Candeias et al. (2020) reported worn brake pads as a source of Cu, whereas material from brake friction, batteries, gasoline, and paint are known to elevate the level of Pb in urban soil and road dust (Adamiec 2017). High concentrations of Ni is possibly associated with sewage waste (Hassaan et al. 2016), fuel combustion and tyre abrasion (Dehghani et al. 2017; Moryani et al. 2020). According to Ali et al. (2017) and Moryani et al. (2020), combustion of lubricants and fuel in an urban environment may possibly be the source of Cr.

Additionally, unregulated burning of waste, unplanned construction, sewage waste and poor waste management practices within the study area may have led to the rise in the level of trace elements such as Co, V and As in soil and road dust. Shi et al. (2017) reported that in an urban environment, the source of Co can be associated with construction dusts from material with cobalt inputs such as alloys and paint. Waste with fertiliser impurities (Hassaan et al. 2016) and oil combustion are considered sources of V (Sager 2020). The possible source of As may be burning of waste (Rybak et al. 2020), sewage, wood preservatives, composts, manures, (Hassaan et al. 2016), metals, and coal burning (Sager 2020). Improper handling of waste materials containing Nb such as electronics, medical equipment, automobile parts (Bilcikova et al. 2018), steel alloys (Schitz et al. 2017) and soil resuspension may intensify the concentration of Nb in urban soil and road dust. Dense traffic, high waste generation, fuel combustion, particularly coal, poor waste management, sewage waste, unregulated waste incineration and unplanned construction are the possible major contributor to the high concentration of trace elements in soil and road dust of Winnie Mandela informal settlement.

The soil samples revealed nine trace elements to be above their average shale values, whereas only six elements were above their average shale values in road dust. According to Hassaan et al. (2016), heavy metals are toxic at high concentrations. The toxicity of trace elements in soil and road dust of this study can be listed as Cr > Co > Zr > Zn > Ni > Cu > Pb > As > Nb and Cr > Ba > Zn > Zr > Cu > Pb, respectively. In this informal settlement, trace elements in soil and road dust may have serious health implications (which are discussed in section 5.6 of this chapter), particularly in children. As reported by Jin et al. (2019), outdoor play areas represent an important exposure situation for children in many urban settlement areas.

Furthermore, the mean concentrations of trace elements observed in the soil and road dust of Winnie Mandela informal settlement were also compared with the mean concentrations of soil and road dust in global urban cities mean(Table 5.4 and Table 5.5). From the literature, 14 publications on urban soils and 18 publications on urban road dust were reviewed. A lot of difference in element concentrations was observed among the trace elements analysed in this study and those in other cities. In soil samples, Sc was higher than those reported in cities such as Istanbul (Sezgin et al. 2019), whereas in road dust it was higher than those observed in Tyumen (Pozhitkov and Ukarkhanova 2021). V in soil samples was higher than those reported in Beijing (Jin et al. 2019), Kumasi (Konwuruk et al. 2021), Hangzhou (Wang and Zhang 2018), Tyumen (Konstantinova et al. 2021), Salerno (Cicchella et al. 2020) and Xi'an (Zhang et al. 2019), whereas in road dust, V was lower than those observed in Xi'an (Li et al. 2019), Ahvaz (Kianpor et al. 2019), and higher than those reported in Tyumen (Pozhitkov and Ukarkhanova 2021), Viana do Castelo (Candeias et al. 2020), Luanda (Ferreira and De Miguel 2005), Seoul (Sager et al. 2015), and Xi'an (Shi et al. 2017).

Cr, with a staggering mean concentration in soil, was also higher than all the reported Cr samples reviewed in world urban cities such as along the Irbid–Zarqa highway in Jordan (Odat 2013), Beijing (Jin et al. 2019), Kumasi (Konwuruk et al. 2021), Fallujah (Salah et al. 2013), Hangzhou (Wang and Zhang 2018), Tyumen (Konstantinova et al.

2019), Salerno (Cicchella et al. 2020), Xi'an (Zhang et al. 2019), Kumasi (Akoto et al. 2017), Ibadan (Odewande and Abimbola 2008), and Suva (Maeaba et al. 2019). In road dust samples, it was also too high as compared to those observed in Tyumen (Pozhitkov and Ukarkhanova 2021), Viana do Castelo (Candeias et al. 2020), Xi'an (Li et al. 2019; Shi et al. 2017), Luanda (Ferreira and De Miguel 2005), Ahvaz (Kianpor et al. 2019), Seoul (Sager et al. 2015), Villavicencio (Trujillo-Gonzalez et al. 2016), Suva (Maeaba et al. 2019), Lublin (Zglobicki et al. 2018), Karachi (Moryani et al. 2020), Jos (Mufuyai et al. 2015), Dhaka (Khan et al. 2018), Dehli (Suryawanshi et al. 2016), Chelyabinsk (Krupnova et al. 2020), Buenos Aires (Fujiwara et al. 2011), and Bolgatanga (Victoria et al. 2014).

The reported Co in soil of this study was lower than those observed by Odat (2013) along the Irbid/Zarqa highway in Jordan. However, it was higher than thos reported in cities such as Beijing (Jin et al. 2019), Kumasi (Konwuruk et al. 2021), Fallujah (Salah et al. 2013), Hangzhou (Wang and Zhang 2018), Tyumen (Kunstantinova et al. 2019), Xi'an (Zhang et al. 2019), Kumasi (Akoto et al. 2017), Havana (Moreno-Alvarez et al. 2020), and Suva (Maeba et al. 2019). In road dust Co was lower than those in Tyumen (Pozhitkov and Ukarkhanova 2021), Xi'an (Shi et. al. 2017), Suva (Maeaba et al. 2019), and higher than the ones observed in cities such as Xi'an (Li et al. 2019), Luanda, (Ferreira and De Miguel 2005), Ahvaz (Kianpor et al. 2019), Seoul (Sager et al. 2015), Chelyabinsk (Krupnova et al. 2020), and Bolgatanga (Victoria et al. 2014).

Ni was lower than those reported in by Odat (2013) along the Irbird/Zarqa highway in Jordan, and higher than those observed in Beijing (Jin et al. 2019), Kumasi (Konwuruk et al. 2021), Fallujah (Salah et al. 2013), Hangzhou (Wang and Zhang 2018), Tyumen (Konstantinova et al. 2019), Salerno (Cicchella et al. 2020), Xi'an (Zhang et al. 2019), Kumasi (Akoto et al. 2017), Ibadan, (Odewande and Abimbola 2008), and Suva (Maeaba et al. 2019). Ni concentration in road dust was found to be lower than those reported in Tyumen (Pozhitkov and Ukarkhanova 2021), Ahvaz (Kianpor et al. 2019), Seoul (Sager et al. 2015), Suva (Maeaba et al. 2019) and Karachi (Moryani et al. 2020), but higher than those in Viana do Castelo (Candeias 2020), Xi'an (Li et al. 2019; Shi et al. 2017), Luanda (Ferreira and De Miguel 2005), Villavicencio (Trujillo-Gonzalez et al. 2016), Lublin (Zglobicki et al. 2018), Jos (Mafuyai et al. 2015), Dhaka

(Khan et al. 2018), Dehli (Suryawanshi et al. 2016), Chelysbinsk (Krupnova et al. 2020), Buenos (Fujiwara et al. 2011), and Bolgatanga (Victoria et al. 2014).

The observed mean concentration of Cu in soil was lower than those reported in Suva city (Maeaba et al. 2019). However, when compared to the ones reported in Dhaka (Rahman et al. 2021), at the Irbird/Zarqa highway in Jordan (Odat 2013), Istanbul (Sezgin et al. 2019), Beijing (Jin et al. 2019), Kumasi (Konwuruk et al. 2021), Falujah (Salah et al. 2013), Hangzhou (Wang and Zhang 2018), Tyumen (Konstantinova et al. 2013), Salerno (Cicchella et al. 2020), Xi'an (Zhang et al. 2019), Kumasi (Akoto et al. 2017), Havana (Moreno-Alvarez et al. 2020), Ibadan (Odawande and Abimbola 2008), and Suva (Maeaba et al. 2019), Cu was found to be higher. In road dust, Cu was lower than the ones reported in Viana do Castelo (Candeias et al. 2020), Seoul (Sager et al. 2015), Villavicencio (Trujillo-Gonzalez et al. 2016), Suva (Maeaba et al. 2019), Lublin (Zglobicki et al. 2018), Karachi (Moryani et al. 2020), Dehli (Suryawanshi et al. 2016), and Buenos Aires (Fujiwara et al. 2011). However, Cu was higher than those observed in Dhaka (Rahman et al. 2021), Tyumen (Pozhitkov and Ukarkhanova 2021), Xi'an (Li et al. 2019; Shi et al. 2017), Luanda (Ferreira and De Miguel 2005), Ahvaz (Kianpor et al. 2019), Jos (Mafuyai et al. 2015), Dhaka (Khan et al. 2018), Chelyabinsk (Krupnova et al. 2020), and Bolgatanga (Victoria et al. 2014).

The reported Zn concentration in soil of this study was lower than the ones reported at the Irbird/Zarqa highway in Jordan (Odat 2013), Istanbul (Sezgin et al. 2019), Hangzhou (Wang and Zhang 2018), Salerno (Cicchela et al. 2020), Kumasi (Akoto et al. 2017), Havana (Moreno-Alvarez et al. 2020), and Suva (Maeaba et al. 2019). When compared to cities such as Dhaka (Rahman et al. 2021), Kumasi (Konwuruk et al. 2021), Fallujah (Sala et al. 2013), Tyumen (Konstantinova et al. 2019), Xi'an (Zhang et al. 2019) and Ibadan (Odewande and Abimbola 2008), Zn was higher than the reported mean concentrations. In road dust, Zn concentrations were lower than the ones in Viano do Castelo (Candeias et al. 2020), Xi'an (Li et al. 2019), Luanda (Ferreira and De Miguel 2005), Ahvaz (Kianpor et al. 2019), Seoul (Sager et al. 2017), Suva (Maeaba et al. 2019), Karachi (Moryani et al. 2020), Lublin (Zglobicki et al. 2018), Dhaka (Khan et al. 2018), Dehli (Suryawanshi et al. 2016), and Buenos Aires (Fujiwara et al. 2018). However, Zn was higher than the ones reported in Dhaka (Rahman et al. 2021), Tyumen (Pozhitkov and Ukarkhanova 2021), Xi'an (Shi et al.

2017), Villavincencio (Trujillo-Gonzalez et al. 2016), Jos (Mafuyai et al. 2015), Chelyabinsk (Krupnova et al. 2020) and Bolgatanga (Victoria et al. 2014).

Arsenic mean concentration in soil of this study was higher than the ones reported in all the reviewed cities which include Dhaka (Rahman et al. 2021), Beijing (Jin et al. 2019), Kumasi (Konwuruk et al. 2021), Tyumen (Konstantinova et al. 2019), Salerno (Cicchella et al. 2020), Xi'an (Zhang et al. 2019), Kumasi (Akoto et al. 2017), Havana (Moreno-Alvarez et al. 2020), and Ibadan (Odewande and Abimbola 2008). In road dust, As was lower than the ones observed in Viana do Castelo (Candeias et al. 2020), Xi'an (Li et al. 2019), Seoul (Sager et al. 2015), and Dhaka (Suryawanshi et al. 2016), but higher than the ones in Tyumen (Pozhitkov and Ukarkhanova 2021), Luanda (Ferreira and De Miguel 2005), Ahvaz (Kianpor et al. 2019), Chelyabinsk (Krupnova et al. 2020), Buenos Aires (Fujiwara et al. 2011), and Bolgatanga (Victoria et al. 2014).

Sr, Rb and Zr in soil samples were lower than the ones reported in Dhaka (Rahman et al. 2021). In road dust, Sr was lower than the ones reported in all reviewed cities such as Dhaka (Rahman et al. 2021), Viana do Castelo (Candeias et al. 2020), Tyumen (Pozhitkov and Ukarkhanova 2021), Xi'an (Li et al. 2019), and Luanda (Ferreira and De Miguel 2005). In soil samples, the reviewed cities had no sufficient data to compare the concentration of Y. However, the concentration of Y in road dust was lower than the ones reported in Xi'an (Li et al. 2019) and higher than those reported in Tyumen (Pozhiktov and Ukarkhanova 2021). Zr was lower than those in Viana do Castelo (Candeias et al. 2020), but greater than those in Dhaka (Rahman et al. 2021), Tyumen (Pozhiktov and Ukarkhanova 2021), and Xi'an (Li et al. 2019). Nb was lower than those observed in road dust of Xi'an (Li et al. 2019) and higher than those witnessed in Tyumen (Pozhitkov and Ukarkhanova 2021). In soil samples there were not enough data for Nb comparison. The concentration of Ba in soil of this study was higher than those reported in Salerno (Cicchella et al. 2020), and Xi'an (Zhang et al. 2019), whereas in road dust, it was lower than those observed in Xi'an (Li et al. 2019), and higher than those in Tyumen (Pozhitkov and Ukarkhanova 2021), Viana do Castelo (Candeias et al. 2020), Luanda (Ferreira and De Miguel 2005)e Seoul (sager et al. 2015).

Lead in soil samples was lower than those recorded in Jordan (Odat 2013), Istanbul (Sezgin et al. 2019), Beijin (Jin et al. 2019), Hangzhou (Wang and Zhang 2018), Salerno (Cicchella et al. 2020), Xi'an (Zhang et al. 2019), Kumasi (Akoto et al. 2017), Havana (Moreno-Alvarez et al. 2020), Ibadan (Odewande and Abimbola 2008), and Suva (Maeaba et al. 2019). However, when the Pb concentration was compared to those in Dhaka (Rahman et al. 2021), Kumasi (Konwuruk et al. 2021) Fallujah (Salah et al. 2013) and Tyumen (Konstantinova et al. 2019), it was found to be higher. In road dust, the concentration of Pb was less than those recorded in Dhaka (Rahman et al. 2021), Tyumen (Candeias et al. 2020), Xi'an (Li et al. 2019; Shi et al. 2015), Luanda (Ferreira and De Muguel 2005), Ahvaz (Kianpor et al. 2019), Seoul (Sager et al. 2017), Villavicencio (Trujillo-Gonzalez et al. 2018), Suva (Maeaba et al. 2019), Lublin (Zglobicki et al. 2018), Karachi (Moryani et al. 2020), Jos (Mafuyai et al. 2015), Dehli (Suryawanshi et al. 2016) and Buenos Aires (Fujiwara et al. 2011), but higher than those reported in Bolgatanga (Victoria et al. 2014), Chelyabinsk (Krupnova et al. 2020), and Dhaka (Khan et al. 2018).

From the 32 reviewed journal manuscripts, the most studied heavy metals in both soil and road dust, namely Cr, Co, Ni, Cu, Zn, As, Pb, Ba and V, whereas Sc, Rb, Sr, Y, Zr, Nb, Th and U were less studied elements. Methods such as flame atomic absorption spectrometry, inductively coupled plasma mass spectrometry, X-ray fluorescence spectrometry, inductively coupled plasma optical emission spectroscopy, and inductively coupled plasma dynamic reaction cell mass spectrometry were found to be mostly utilised to analyse the concentration of heavy metals, whereas in this study, WD- X-ray fluorescence spectrometry was used. Most of the studies were conducted in major urban cities, compared to the present study which was conducted in a poor urban informal settlement. In general, the mean concentration of trace elements in soil and road dust of Winnie Mandela informal settlement were slightly higher than those reported in other urban global cities.

Cr in the soil of Winnie Mandela informal settlement showed an astonishing high concentration (1 070 mg/kg), which was higher than those reported in other cities and higher than the concentration of all the trace elements in soil. U, in this study, recorded the lowest concentration (3.2 mg/kg) in soil when compared to all the reported concentrations of trace elements in other reviewed urban cities. In road dust, the concentration of Zn (4254.4 mg/kg) in Karachi (Pakistan) was very high when compared to the Zn concentration observed in this study and other urban cities, whereas U in Luanda (Angola) had the lowest mean concentration (1.0 μgg^{-1}) when compared to the findings of this study and other cities.

According to Salah et al. (2013), variations in mean concentrations of trace elements may have been influenced by different characteristics such as geology of the area, traffic concentrations and the type of man-made activities. In this study, dense traffic and human activities such as high population, unplanned construction, poor waste management, unregulated waste incineration, fuel combustion, particularly coal and sewage waste that runs out onto the streets, may be considered as the major contributors to the concentration of heavy metals. Urban population levels and stages of development may also affect the concentration of heavy metals (Shi et al. 2017).

Furthermore, high concentrations of trace elements in this study can also be attributed to the method of sampling and analytical method used (WD-XRF) for the analysis of trace elements. According to Ma and Singhirunnusorn (2012), factors such as selection of sampling area and method of sampling, may contribute to the variation of mean concentrations of trace elementsmean. They also stressed that analytical methods used in different urban cities may lead to changes in concentrations of heavy metals (Ma and Singhirunnusorn 2012).

Table 5.4 Comparison of trace elements in soil with other global cities

City and country	Trace elements in soil (mg/kg)																	Reference
	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U	
Winnie Mandela (South Africa)	13.0	178.8	1070.0	46.8	86.0	85.8	104.2	18.8	66.6	62.2	17.4	237.6	12.8	573.2	25.8	7.4	3.2	This study
Dhaka city (Bangladesh)	–	–	–	–	–	40.2	77.0	16.6	115.9	186.1	–	253.8	–	–	19.5	–	–	(Rahman et al. 2021)
Ibird/Zaqa (Jordan)	–	–	67.4	506.0	926.2	27.7	193.3	–	–	–	–	–	–	–	48.0	–	–	(Odat 2013)
Istanbul (Turkey)	3.6	–	–	–	–	50.5	122.6	–	–	–	–	–	–	–	34.3	–	–	(Sezgin et al. 2019)
Beijing (China)	–	110.7	54.7	12.6	33.7	43.4	–	15.6	–	–	–	–	–	–	36.6	–	–	(Jin et al. 2019)
Kumasi (Ghana)	–	78.2	77.9	–	29.3	20.2	49.3	10.1	–	–	–	–	–	–	18.6	–	–	Konwuruk et al. 2021)
Fallujah (Iraq)	–	–	11.6	3.4	9.0	2.0	5.5	–	–	–	–	–	–	–	3.8	–	–	(Salah et al. 2013)
Hangzhou (China)	–	48.6	53.3	7.3	22.9	38.7	139.0	–	–	–	–	–	–	–	70.0	–	–	(Wang and Zhang 2018)
Tyumen (Russia)	–	95.0	107.0	19.5	44.0	39.0	70.0	7.7	–	–	–	–	–	–	19.6	–	–	(Konstantinova et al. 2019)
Salerno (Italy)	-	55.0	17.2	-	15.3	60.6	129.0	10.4	-	-	-	-	-	284.0	67.0	–	–	(Cicchella et al. 2020)
Xi'an (China)	–	79.0	69.0	23.0	31.1	29.4	90.0	12.7	-	-	-	-	-	560.0	32.2	–	–	(Zhang et al. 2019)
Kumasi (Ghana)	–	–	97.4	4.0	20.4	43.1	107.0	1.5	–	–	–	–	–	–	52.8	–	–	(Akoto et al. 2017)
Havana (Cuba)	–	–	82.9	11.7	72.1	73.5	126.0	8.1	–	–	–	–	–	–	73.5	–	–	(Moreno-Alvarez et al. 2020)
Ibadan (Nigeria)	–	–	56.0	-	16.5	32.0	94.0	3.0	–	–	–	–	–	–	47.0			(Odewande and Abimbola 2008)
Suva(Fiji)	–	–	34.0	33.2	32.4	265.7	507.0	–	–	–	–	–	–	–	59.3			(Maeba et al. 2019)

Table 5.5 Comparison of trace elements in road dust with other global cities

City and country	Trace elements in road dust (mg/kg)																	Reference
	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U	
Winnie Mandela (South Africa)	5.8	69.0	637.4	17.4	49.0	61.0	231.8	7.2	66.0	120.2	14.4	190.2	8.6	625.6	30.8	4.6	2.9	This study
Dhaka city (Bangladesh)	–	–	–	–	–	59.3	189.0	–	88.1	289.9	–	165.6	–	–	59.6	–	–	(Rahman et al. 2021)
Tyumen (Russia)	10.1	66.4	507.9	39.6	632.1	57.4	160.8	5.7	27.1	147.3	7.3	60.7	6.6	317.1	33.9	1.9	1.1	(Pozhitkov and Ukarkhanova 2021)
Viana do Castelo (Portugal)	–	15.0	210.0	–	16.0	260.0	1180.0	35.0	240.0	190.0	–	360.0	–	390.0	86.0	–	3.6	(Candeias et al. 2020)
Barbican Downtown (China)	–	69.3	175.2	13.7	21.0	50.9	272.0	11.7	44.2	186.5	18.6	120.1	11.9	748.2	93.5	–	–	(Li et al. 2019)
Luanda (Angola)	1.3	20.0	26.0	2.9	10.0	42.0	317.0	5.0	–	172.0	–	–	–	131.0	351.0	1.7	1.0	(Ferreira and De Miguel 2005)
Ahvaz (Iran)	–	184.0	57.0	13.0	58.0	45.0	999.0	6.0	–	–	–	–	–	–	86.0	–	–	(Kianpor et al. 2019)
Seoul (Korea)	–	35.0	130.0	17.9	62.0	351.0	1476.0	24.9	–	–	–	–	–	570.0	214.0	–	–	(Sager et al. 2015)
Xi'an (China)	–	55.8	175.3	34.1	28.3	48.9	164.9	–	–	–	–	–	–	–	97.6	–	–	(Shi et al. 2017)
Villavicencio (Columbia)	–	–	9.4	–	5.3	126.3	133.3	–	–	–	–	–	–	–	87.5	–	–	(Trujillo-Gonzalez et al. 2016)
Suva (Fiji)	–	–	40.0	35.0	54.0	172.0	685.0	–	–	–	–	–	–	–	54.0	–	–	(Maeaba et al. 2019)
Lublin (Poland)	–	–	86.4	–	16.5	81.6	241.1	–	–	–	–	–	–	–	44.1	–	–	(Zglobicki et al. 2018)

City and country	Trace elements in road dust (mg/kg)																	Reference
	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U	
Karachi (Pakistan)	–	–	148.1	–	389.7	332.9	4254.4	–	–	–	–	–	–	–	426.6	–	–	(Moryani et al. 2020)
Jos (Nigeria)	–	–	2.0	–	1.2	56.5	72.0	–	–	–	–	–	–	–	61.0	–	–	(Mafuyai et al. 2015)
Dhaka (Bangladesh)	–	–	144.3	–	37.0	49.7	239.2	8.1	–	–	–	–	–	–	19.0	–	–	(Khan et al. 2018)
Dehli (India)	–	–	149.0	–	36.0	192.0	285.0	–	–	–	–	–	–	–	121.0	–	–	(Suryawanshi et al. 2016)
Chelyabinsk (Russia)	–	–	49.0	6.3	21.9	56.0	154.0	3.8	–	–	–	–	–	–	21.9	–	–	(Krupnova et al. 2020)
Buenos Aires (Argentina)	–	–	–	–	26.2	273.0	766.0	5.5	–	–	–	–	–	–	296.0	–	–	(Fujiwara et al. 2011)
Bolgatanga (Ghana)	–	–	4.2	2.4	2.3	12.6	4.1	0.2	–	–	–	–	–	–	4.9	–	–	(Victoria et al. 2014)

5.4 Assessment of pollution levels and sources identification of trace elements in soil and road dust

The Pearson's correlation coefficient and ANOVA was performed to assess the degree of contamination and identify the possible sources of trace elements in both soil and road dust of Winnie Mandela informal settlement. Furthermore, the study also utilised pollution indices such as Igeo, CF, PLI and EF. The pollution indices were calculated using Equations 1, 2, 3 and 4, described in Chapter 4.

5.4.1 Pearson correlation coefficient analysis

Pearson's correlation coefficient was performed to establish the relationships of trace elements and determine their common source of origin in both soil and road dust samples. The correlation matrix of trace elements in both soil and road dust samples generated a diverse relationship between elements. From the correlation analysis, a very high positive correlation, sufficiently high degree of correlation, moderate degree, and no positive correlation results were observed in soil, whereas in road dust a sufficiently high degree of correlation, moderate degree, and no positive correlation results were observed. The results of the trace elements correlation analysis in soil and road dust are summarised in Tables 5-6 and 5-7, respectively.

A very high positive correlation was witnessed between pairs of Y to Sr (r=0.94), Zr to As (r=0.90), Pb to As (r=0.92) and Pb to Zr (r=0.95) in soil samples. A sufficiently high degree of correlation happened between Ni to Cr (r=0.89), Sr to Rb (r=0.85), Nb to Co (r=0.75), Nb to Rb (r=0.85), Th to Y (r=0.87) and U to Zn (r=0.89). The results also display a moderate degree of correlation for elements such as V to Sc (r=0.69), Cu to Sc (r=0.73), As to Co (r=0.62), Y to Rb (r=0.72), Ba to Zr (0.62), Th to Sr (r=0.67) and U to Ba (0.70). Absence of correlation was observed between Rb and V (r=0.00).

In road dust samples, a very high positive correlation was witnessed between pairs of Ni to Cr (0.97) and Zn to Cu (r=0.99). Pairs of Co to V (r=0.83), Co to Cr (r=0.89), Ni to Co (r=0.81), As to Sc (r=0.78), Sr to Sc (r=0.88), Sr to As (r=0.88), Zr to V (r=0.81), Pb to Cr (r=0.89), Pb to Co (r=0.87), and Pb to Ni (0.77) showed a sufficiently high degree of correlation. The results also displayed a moderate degree of correlation for elements such as Cr to V (r=0.67), Sr to Zn (r=0.65), Y to Cu (r=0.67), Y to Zn (r=0.61), Ba to Co (r=0.67), Pb to V (r=0.65), and Th to Sc (0.66). U showed no positive correlation (r=0.00) with all the elements.

According to Weissmannova et al. (2019), high correlations among heavy metals refer to the same source of pollution or anthropogenic sources, whereas low or negative correlation signifies a different origin or refers to natural sources. Therefore, the high degree of correlation of elements such as Y to Sr, Zr to As, Pb to As, Pb to Zr,, Ni to Cr, Sr to Rb, Nb to Co, Nb to Rb, Th to Y, U to Zn, in soil samples and Ni to Cr, Zn to Cu, Co to V, Co to Cr, Ni to Co, As to Sc, Sr to Sc, Sr to As, Zr to V, Pb to Cr, Pb to Co, Pb to Ni in road dust of this study signified an identical source of pollution, possibly from anthropogenic activities. The anthropogenic sources of these trace elements in soil and road dust from Winnie Mandela informal settlement can possibly be associated with dense traffic and man-made activities such as sewage waste that are exposed on the streets, high population, high waste generation, coal fly ash, poor waste management, unregulated waste incineration and unplanned construction.

The anthropogenic contribution of Zn in an urban environment is linked to tyre rubber, brake ware, resuspended particles, burning of fuel (Candeias et al. 2020), and sewage (Hassaan et al. 2016). Ni is possibly associated with sewage (Hassaan et al. 2016), burning of fuel and abrasion of tires (Dehghani et al. 2017; Moryani et al. 2020). Corrosion of vehicle parts (Victoria et al. 2014), combustion of lubricants and fuel (Ali et al. 2017; Moryani et al. 2020) are the major contributors of Cr in an urban environment. According to Chen et al. (2015), Zr is possibly emanated from vehicle exhaust fumes due to its use as zirconia (ZrO_2) in catalysts. Furthermore, Candeias et al. (2020) reported that wearing of brake pads are the possible source of Cu. Sewage waste (Hassaan et al. 2016), materials from brake frictions, batteries, gasoline, and paint are known to elevate the level of Pb in urban soil and road dust (Adamiec 2017; Candeias et al. 2020).

Furthermore, the source of Co may probably be linked to the construction materials with cobalt inputs such as alloys and paint, which end up being deposited in soil and road dust (Shi et al. 2017). Waste, containing fertiliser impurities (Hassaan et al. 2016), electronics, dyeing (Yang et al. 2016) and oil combustion, are contributors of V in urban areas (Sager 2020). The possible source of As can be attributed to waste burning (Rybak et al. 2020), wood preservatives, sewage, composts, manures

(Hassaan et al. 2016), metals, and coal burning (Sager 2020). Improper handling of these materials may lead to As being deposited in soil and road dust. A trace element such as Sc is considered to be a natural element and its occurrence in the road dust suggests the vehicle resuspension of road dust (Yalala 2015). According to Rahman et al. (2021), coal burning and oil burning are some of the sources of Sr. The concentration of Nb, U, and Y in road dust is understood to be contributed by soil resuspension as they are crustal elements, whereas emitted brake ware dust is usually associated with Rb (Li et al. 2019). Coal combustion together with soil resuspension may increase the concentration of Th in urban soil and road dust (Charlesworth et al. 2011).

Table 5.6 Correlation matrix of trace elements in soil

Elements	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U
Sc	1																
V	**0.69**	1															
Cr	-0.21	0.36	1														
Co	0.17	0.26	-0.55	1													
Ni	0.11	0.59	**0.89**	-0.48	1												
Cu	**0.73**	0.03	-0.75	0.19	-0.50	1											
Zn	-0.32	-0.88	-0.75	0.01	-0.80	0.40	1										
As	-0.08	0.19	-0.06	**0.62**	-0.32	-0.19	-0.24	1									
Rb	-0.22	0.00	-0.14	0.32	0.10	-0.17	0.11	-0.38	1								
Sr	-0.22	0.03	0.26	-0.19	0.50	-0.32	-0.07	-0.69	**0.85**	1							
Y	0.09	0.17	0.21	-0.30	0.55	-0.05	-0.11	-0.84	**0.72**	**0.94**	1						
Zr	-0.40	-0.26	-0.14	0.41	-0.52	-0.25	0.11	**0.90**	-0.45	-0.72	-0.92	1					
Nb	-0.10	0.20	-0.28	**0.75**	-0.10	-0.14	-0.03	0.13	**0.85**	0.50	0.32	-0.05	1				
Ba	-0.91	-0.79	0.07	-0.19	-0.33	-0.54	0.45	0.25	-0.15	-0.17	-0.43	**0.62**	-0.18	1			
Pb	-0.45	-0.07	0.12	0.41	-0.26	-0.49	-0.15	**0.92**	-0.33	-0.56	-0.80	**0.95**	0.07	0.58	1		
Th	0.55	0.41	-0.01	-0.16	0.43	0.37	-0.16	-0.77	0.51	**0.67**	**0.87**	-0.96	0.22	-0.78	-0.91	1	
U	-0.58	-0.98	-0.36	-0.38	-0.54	0.07	**0.89**	-0.32	-0.04	-0.02	-0.09	0.12	-0.30	**0.70**	-0.08	-0.29	1

Coefficients above 0.6 are in bold red.

Table 5.7 Correlation matrix of trace elements in road dust

Elements	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U
Sc	1																
V	-0.91	1															
Cr	-0.72	**0.67**	1														
Co	-0.70	**0.83**	**0.89**	1													
Ni	-0.63	0.56	**0.97**	**0.81**	1												
Cu	0.37	-0.49	-0.27	-0.34	-0.37	1											
Zn	0.42	-0.57	-0.35	-0.46	-0.43	**0.99**	1										
As	**0.78**	-0.55	-0.82	-0.55	-0.86	0.36	0.37	1									
Rb	**0.63**	-0.58	-0.20	-0.32	0.01	-0.33	-0.28	0.16	1								
Sr	**0.88**	-0.85	-0.90	-0.85	-0.89	0.59	**0.65**	**0.85**	0.24	1							
Y	0.11	0.04	-0.23	0.04	-0.43	**0.67**	**0.61**	0.56	-0.63	0.38	1						
Zr	-0.75	**0.81**	0.14	0.36	0.02	-0.40	-0.42	-0.24	-0.70	-0.47	0.16	1					
Nb	-0.39	0.30	-0.15	-0.04	-0.34	0.47	0.46	0.06	-0.93	0.09	0.67	**0.61**	1				
Ba	-0.03	0.29	0.54	**0.67**	0.59	-0.48	-0.56	-0.12	0.43	-0.46	-0.21	-0.21	-0.70	1			
Pb	-0.66	**0.65**	**0.89**	**0.87**	**0.77**	0.11	0.00	-0.59	-0.51	-0.70	0.23	0.18	0.19	0.38	1		
Th	**0.66**	-0.86	-0.78	-0.97	-0.70	0.47	0.58	0.42	0.28	0.82	-0.05	-0.44	0.08	-0.71	-0.75	1	
U	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1

Coefficients above 0.6 are in bold red.

5.4.2 One-way Analysis of Variance

One-way ANOVA was performed to test the difference between the concentration of elements in soil and road dust samples. The P-value in soil samples was 1.24E-12, whereas in the road dust sample it was 5.09E-20, as shown in Table 5.8. In both soil and road dust samples, the P-values were less than the alpha level 0.05 ($P < 0.05$).

The ANOVA results of the analysed trace elements in this study showed significant differences ($P < 0.05$) in all the trace elements determined in soil and road dust. These findings clearly indicate that the trace elements pollutants in both soil and road dust were not from the common anthropogenic sources that is comparable with the study conducted in Yola, Nigeria, which also found significant differences for all heavy metals in road dust (Shinggu et al. 2009). In this informal settlement, vehicle emissions and anthropogenic activities such as poor waste management activities, sewage waste, burning of coal, unplanned construction and unregulated waste burning, can be considered as the source of these trace elements.

Table 5.8 Single factor Analysis of Variance of concentrations of trace elements in soil and road dust

Analysis of Variance in soil						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between groups	5 995 670	16	374 729.4	10.37824	**1.24E-12**	1.794556
Within groups	2 455 292	68	36 107.23			
Total	8 450 961	84				
Analysis of Variance in road dust						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between groups	3 245 171	16	202 823.2	20.62999	**5.09E-20**	1.794556
Within groups	668 540.3	68	9 831.475			
Total	3 913 712	84				

*SS= sum of squares; df= degree of freedom; MS= mean squares; F= variation ratio; P:-value= probability value; F crit = critical value.

5.4.3 Geo-accumulation index

Igeo was used to explain the quality of soil and road dust. In this study, the average shale value for each trace element was considered as the background concentration as described by Turekian and Wedepohl (1961). The results of Igeo for all the analysed elements in soil were presented as minimum, maximum and mean in Table 5.9. The minimum and maximum values of Igeo ranged from Sr (0.03 to 0.06), Cr (1 to 5.25), Rb (0.07 to 0.14), Co (0.4 to 0.57), Th (0.05 to 0.16), Cu (0.26 to 0.59), Y (0.08 to 0.17), Zr (0.28 to 0.33), U (0.16 to 0.26), V (0.23 to 0.3), Sc (0.17 to 0.25), As (0.15 to 0.64), Ba (0.16 to 0.24), Pb (0.09 to 0.7), Zn (0.14 to 0.32), Ni (0.17 to 0.42, and Nb (0.22 to 0.3). Their mean concentrations were 0.04, 2.4, 0.1, 0.5, 0.12, 0.38, 0.13, 0.3, 0.18, 0.3, 0.2, 0.29, 0.2, 0.26, 0.22, 0.25, and 0.23, respectively.

Table 5.9 Geo-accumulation values of trace element contaminations in soil for Winnie Mandela informal settlement

Geo-accumulation values of heavy metals in soil samples				
Elements	**Minimum**	**Maximum**	**Mean**	**Classification**
Cr	1	5.25	2.4	Moderately to heavily contaminated
Co	0.4	0.57	0.5	Uncontaminated to moderately contaminated
Cu	0.26	0.59	0.38	Uncontaminated to moderately contaminated
Zr	0.28	0.33	0.3	Uncontaminated to moderately contaminated
V	0.23	0.3	0.3	Uncontaminated to moderately contaminated
As	0.15	0.64	0.29	Uncontaminated to moderately contaminated
Pb	0.09	0.7	0.26	Uncontaminated to moderately contaminated
Ni	0.17	0.42	0.25	Uncontaminated to moderately contaminated
Nb	0.22	0.3	0.23	Uncontaminated to moderately contaminated
Zn	0.14	0.32	0.22	Uncontaminated to moderately contaminated
Ba	0.16	0.24	0.2	Uncontaminated to moderately contaminated
Sc	0.17	0.25	0.2	Uncontaminated to moderately contaminated
U	0.16	0.26	0.18	Uncontaminated to moderately contaminated
Y	0.08	0.17	0.13	Uncontaminated to moderately contaminated
Th	0.05	0.16	0.12	Uncontaminated to moderately contaminated
Rb	0.07	0.14	0.1	Uncontaminated to moderately contaminated
Sr	0.03	0.06	0.04	Uncontaminated to moderately contaminated

As summarised in Table 5.10, the concentration values of Igeo in road dust samples ranges between Cr (0.63 and 2.42), Th (0.05 and 0.09), Zn (0.14 and 1.47), Sr (0.05 and 0.1), Pb (0.17 and 0.41), Rb (0.08 and 0.12), Cu (0.19 and 0.55), Sc (0.06 and 0.12), V (0.08 and 0.13), Zr (0.12 and 0.28), As (0.06 and 0.15), Ba (0.19 and 0.24), Y (0.1 and 0.11), Co (0.16 and 0.21), Ni (0.09 and 0.23), U (0.16 and 0.16), and Nb

(0.14 and 0.16) with mean concentrations of 1.42, 0.08, 0.49, 0.08, 0.31, 0.09, 0.27, 0.09, 0.1, 0.24, 0.11, 0.21, 0.11, 0.2, 0.14, 0.16, and 0.16, correspondingly.

Table 5.10 Geo-accumulation values of trace element contaminations in road dust for Winnie Mandela informal settlement

Geo-accumulation values of heavy metals in road samples				
Elements	**Minimum**	**Maximum**	**Mean**	**Classification**
Cr	0.63	2.42	1.42	Moderately contaminated
Zn	0.14	1.47	0.49	Uncontaminated to moderately contaminated
Pb	0.17	0.41	0.31	Uncontaminated to moderately contaminated
Cu	0.19	0.55	0.27	Uncontaminated to moderately contaminated
Zr	0.12	0.28	0.24	Uncontaminated to moderately contaminated
Ba	0.19	0.24	0.21	Uncontaminated to moderately contaminated
Co	0.16	0.21	0.2	Uncontaminated to moderately contaminated
U	0.16	0.16	0.16	Uncontaminated to moderately contaminated
Nb	0.14	0.16	0.16	Uncontaminated to moderately contaminated
Ni	0.09	0.23	0.14	Uncontaminated to moderately contaminated
Y	0.1	0.11	0.11	Uncontaminated to moderately contaminated
As	0.06	0.15	0.11	Uncontaminated to moderately contaminated
V	0.08	0.13	0.1	Uncontaminated to moderately contaminated
Sc	0.06	0.12	0.09	Uncontaminated to moderately contaminated
Rb	0.08	0.12	0.09	Uncontaminated to moderately contaminated
Sr	0.05	0.1	0.08	Uncontaminated to moderately contaminated
Th	0.05	0.09	0.08	Uncontaminated to moderately contaminated

The average Igeo value revealed that soil was moderately to heavily contaminated by Cr ($2 < \text{Igeo} \leq 3$) which is higher than those reported in Suva City, Fiji (Maeaba et al. 2019) and Ijebu-Ode, Nigeria (Adedeji et al. 2019), who observed soil to be uncontaminated by Cr and uncontaminated to moderately contaminated by Cr, respectively. Furthermore, the soil was uncontaminated to moderately contaminated by Co, Cu, Zr, V, As, Pb, Ni, Nb, Zn, Ba, Sc, U, Y, Th, Rb and Sr ($0 < \text{Igeo} \leq 1$), which is in agreement with the findings of the study conducted in Dongguan, China (Liu et al. 2016), which reported soil to be uncontaminated to moderately contaminated by Ni and Cu in Dhaka, Bangladesh (Ahmed et al. 2016), which witnessed roadside soil to be uncontaminated to moderately contaminated by Sr and Ba, and in Dhaka city, Bangladesh (Rahman et al. 2021), which revealed soil to be uncontaminated to moderately contaminated by Zn, Rb, and Zr.

Moreover, the average Igeo values also showed that road dust in Winnie Mandela informal settlement was moderately contaminated by Cr (1 < Igeo ≤ 2), which correspond with the study by Shi et al. (2017), who reported road dust in Xi'an, China, to be moderately contaminated by Cr. Additionally, road dust was also uncontaminated to moderately contaminated by Co, Cu, Zr, V, As, Pb, Ni, Nb, Zn, Ba, Sc, U, Y, Th, Rb and Sr (0< Igeo ≤ 1), which is similar to the findings of the study conducted in Xi'an, China (Shi et al. 2017), which observed road dust to be uncontaminated to moderately contaminated by Zn, and Cu; in the Maha Sarakham municipality, Thailand (Ma and Singhirunnusorn 2012), which reported road dust to be uncontaminated to moderately contaminated by Cu; in Tianshui, China (Tan et al. 2021), which witnessed road dust to be uncontaminated to moderately contaminated by Cu and As, and in Dhaka city, Bangladesh (Rahman et al. 2021), which discovered road dust to be uncontaminated to moderately contaminated by Rb. These findings clearly show that the level of pollution by trace elements in Winnie Mandela informal settlement and soil and road dust other cities is a serious problem.

Furthermore, the inclusive Igeo index values in soil and road dust show the following descending patterns: Cr > Co > Cu > Zr > V > As > Pb > Ni > Nb > Zn > Ba > Sc > U > Y > Th > Rb > Sr and Cr > Zn > Pb > Cu > Zr > Ba > Co > U > Nb > Ni > Y > As > V > Sc > R b > Sr > Th, respectively. As depicted in Figure 5.6, Cr was the leading element in both soil and road dust, indicating possible anthropogenic sources, which may be associated with dense traffic in this informal settlement. There is evidence that associate the rise of Cr concentration in an urban environment with the corrosion of vehicle parts (Victoria et al. 2014), and combustion of lubricants and fuel (Ali et al. 2017; Moryani et al. 2020). Additionally, the results of geo-accumulation suggest that Co, Cu, Zr, V, As, Pb, Ni, Nb, Zn, Ba, Sc, U, Y, Th, Rb and Sr in soil and road dust were of a natural source, with a slight influence of anthropogenic activities. The natural source of these elements may possibly be associated with wind-borne soil particles, precipitation, geological weathering or erosion (Maeaba et al. 2019). On the basis of Igeo average values, Cr in soil and road dust is an element of concern to the population of Winnie Mandela informal settlement.

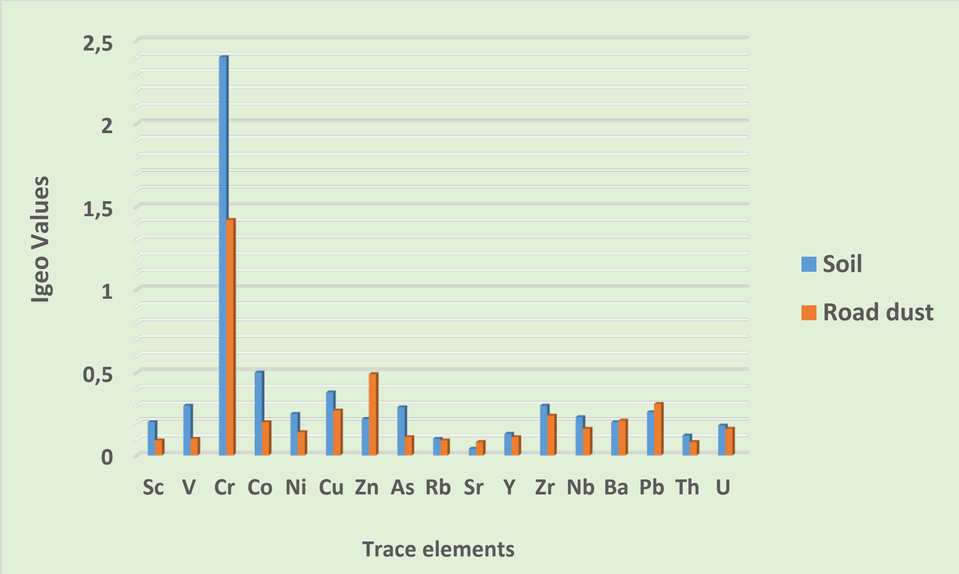

Figure 5.6 Trace element contamination level in soil and road dust based on Igeo values

5.4.4 Contamination factor

To calculate the CF of various trace elements in soil and road dust, the average shale values were utilised as a background concentration, as described by Turekian and Wedepohl (1961). The CF results in soil are presented in Table 5.11. The contamination factor values ranged from Cr (5.02 to 25.66), Co (2 to 2.84), Cu (1.29 to 2.84), Zr (1.40 to 1.65), As (0.77 to 3.23), V (1.15 to 1.47), Ni (0.87 to 2.09), Pb (0.45 to 3.5), Nb (1.09 to 1.36), Zn (0.69 to 1-59), Sc (0.85 to 1.23), Ba (0.77 to 1.21), U (0.78 to 1.08), Y (0.42 to 0.85), Th (0.24 to 5.83), Rb (0.37 to 0.69), and Sr (0.14 to 0.29). Their respective CF mean values were 11.9, 2.5, 1.91, 1.50, 1.45, 1.40, 1.30, 1.30, 1.20, 1.10, 1.0, 0.99, 0.86, 0.70, 0.61, 0.50, and 0.21.

Table 5.11 Contamination factors and pollution load index values of trace elements in soil of Winnie Mandela settlement

Contamination factors and pollution load index values of trace elements in soil samples				
Elements	**Minimum**	**Maximum**	**Mean**	**Classification**
Cr	5.02	25.66	11.9	Very high contamination
Co	2	2.84	2.5	Moderate contamination
Cu	1.29	2.98	1.91	Moderate contamination
Zr	1.4	1.65	1.5	Moderate contamination
As	0.77	3.23	1.45	Moderate contamination
V	1.15	1.47	1.4	Moderate contamination
Ni	0.87	2.09	1.3	Moderate contamination
Pb	0.45	3.5	1.3	Moderate contamination
Nb	1.09	1.36	1.2	Moderate contamination
Zn	0.69	1.59	1.1	Moderate contamination
Sc	0.85	1.23	1	Moderate contamination
Ba	0.77	1.21	0.99	Low contamination
U	0.78	1.08	0.86	Low contamination
Y	0.42	0.85	0.7	Low contamination
Th	0.24	5.83	0.61	Low contamination
Rb	0.37	0.69	0.5	Low contamination
Sr	0.14	0.29	0.21	Low contamination
PLI	0.23	3520.8	65.24	Very highly polluted

As summarised in Table 5.12, the CF minimum and maximum values in road dust ranged from Cr (3.14 to 12.08), Zn (0.70 to 7.37), Pb (0.85 to 2.05), Cu (0.93 to 2.78), Zr (1.02 to 1.42), Ba (0.94 to 1.26), Co (0.94 to 1.05), U (0.78 to 0.78), Nb (0.72 to 0.81), Ni (0.47 to 1.18), As (0.31 to 0.77), Y (0.54 to 0.58), V (0.42 to 0.63), Rb (0.40 to 0.58), Sc (0.31 to 0.61), Sr (0.27 to 0.52), and Th (0.02 to 0.50), with mean values of 7.08, 2.44, 1.54, 1.35, 1.20, 1.08, 0.91, 0.80, 0.80, 0.72, 0.55, 0.55, 0.53, 0.47, 0.45, 0.40, and 0.38, correspondingly.

Table 5.12 Contamination factors and pollution load index values of trace elements in road dust of Winnie Mandela settlement

Contamination factors and pollution load index values of trace elements in road dust samples				
Elements	**Minimum**	**Maximum**	**Mean**	**Classification**
Cr	3.14	12.08	7.08	Very high contamination
Zn	0.7	7.37	2.44	Moderate contamination
Pb	0.85	2.05	1.54	Moderate contamination
Cu	0.93	2.78	1.35	Moderate contamination
Zr	1.02	1.42	1.2	Moderate contamination
Ba	0.94	1.26	1.08	Moderate contamination
Co	0.79	1.05	0.91	Low contamination
U	0.78	0.78	0.8	Low contamination
Nb	0.72	0.81	0.8	Low contamination
Ni	0.47	1.18	0.72	Low contamination
As	0.31	0.77	0.55	Low contamination
Y	0.54	0.58	0.55	Low contamination
V	0.42	0.63	0.53	Low contamination
Rb	0.4	0.58	0.47	Low contamination
Sc	0.31	0.61	0.45	Low contamination
Sr	0.27	0.52	0.4	Low contamination
Th	0.02	0.5	0.38	Low contamination
PLI	0.68	72.9	5.37	Very highly polluted

CF was used to interpret the degree of trace element pollution in the soil and road dust samples of Winnie Mandela informal settlement (Alsafran et al. 2021). The CF mean values in soil revealed three different classes of contamination. Only Cr was found to be above six (CF > 6), indicating a very high contamination clearly from anthropogenic activities which is comparable to the findings in the Kumasi Metropolis soil, Ghana (Akoto et al. 2017), which witnessed Cr to be above six, indicating very high contamination. Trace elements such as Co, Cu, Zr, As, V, Ni, Pb, Nb, Zn and Sc were between ($1 \leq CF \leq 3$), signifying moderate contamination from a natural origin, with a slight influence of anthropogenic activities that is similar to the results reported in Botswana (Mmolawa et al. 2011), which classified Cu, Ni, and Pb in Zone NM soils along the major roadsides, to be of moderate contamination. Unlike the results of this study in peri-urban topsoil of the Kumasi Metropolis, Ghana, Konwuruk et al. (2021)

reported low contamination of soil by elements such as As, Pb, Cu, Ni, V, and Zn. Furthermore, low contamination (CF < 1) was reported for trace elements such as Ba, U, Y, Th, Rb and Sr, which indicates a natural origin.

Moreover, the CF mean value for Cr in road dust was above six (CF > 6), indicating a very high contamination from man-made activities that surpass the findings of Dat et al. (2021) in street dust of a metropolitan area of Southern Vietnam, which recorded considerable contamination of soil by Cr. Moderate contamination (1 ≤ CF ≤ 3) was noted for elements such as Zn, Pb, Cu, Zr and Ba, signifying a natural origin, with moderate influence of anthropogenic activities that support the findings of Al-Dabbas et al. (2018), who also witnessed moderate contamination of Pb and Zn in street dust of Diwaniya, Iraq. The majority of trace elements such as Co, U, Nb, Ni, As, Y, V, Rb, Sc, Sr, and Th, were classified as low contamination, resembling a natural origin and agrees with the study conducted in the Bolgatanga municipality, Ghana (Victoria et al. 2014), which observed low contamination of Co, Ni, and As in road dust. Low contamination of V in street dust of Diwaniya, Iraq, was reported by Al-Dabbas et al. (2018) and in Dhaka city, Bangladesh, Kabir et al. (2021) reported low contamination of road dust by Co.

Additionally, in both soil and road dust, Cr was the major pollution contributor among the heavy metals (Figure 5.7) and highest in soil. The overall contamination factor and mean values of various trace elements in soil and road dust were orderly decreasing as Cr > Co > Cu > Zr > As > V > Ni > Pb > Nb > Zn > Sc > Ba > U > Y > Th > Rb > Sr and Cr > Zn > Pb > Cu > Zr > Ba > Co > U > Nb > Ni > As > Y > V > Rb > Sc > Sr > Th, respectively. The results of the CF revealed that trace elements such as Ba, U, Y, Th, Rb, Sr in soil and Co, U, Nb, Ni, As, Y, V, Rb, Sc, Sr and Th in road dust were probably from a natural origin such as resuspended soil particles, precipitation, geological weathering or erosion (Maeaba et al. 2019). However, there was a slight influence of trace elements such as Co, Cu, Zr, As, V, Ni, Pb, Nb, Zn and Sc in soil and Zn, Pb, Cu, Zr and Ba in road dust by man-made activities. Furthermore, CF results exhibited Cr in both soil and road dust to be of anthropogenic origin.

The man-made activities that may have influenced the contamination level of the trace elements in this study is understood to be through traffic, poor waste management, coal fly ash, sewage waste, unregulated waste burning, and unplanned construction.

According to Chen et al. (2015), Zr is possibly from vehicle exhaust fumes, Zn may have been influenced by sewage or tyre rubber (Candeias et al. 2020; Hassaan et al. 2016), Ni is associated with sewage and tyre abrasion (Dehghani et al. 2017; Hassaan et al. 2016; Moryani et al. 2020), Cr by corrosion of vehicle parts, and combustion of lubricants and fuel (Victoria et al. 2014), Cu from worn brake pads (Candeias et al. 2020), Pb from sewage, gasoline and paint (Adamiec 2017; Candeias et al. 2020; Hassaan et al. 2016). Co may probably be from alloys and paint (Shi et al. 2017), V from oil combustion (Sager 2020), As may be from waste burning (Rybak et al. 2020), and Sc from the vehicle resuspension of road dust (Yalala 2015). According to the results of CF, anthropogenic activities in Winnie Mandela informal settlement have exacerbated the concentration of Cr in both soil and road dust, which agrees with the results of the Igeo accumulation index. These outcomes demonstrated Cr to be an element of public concern in Winnie Mandela informal settlement, and remediation and regular monitoring are thus highly advocated.

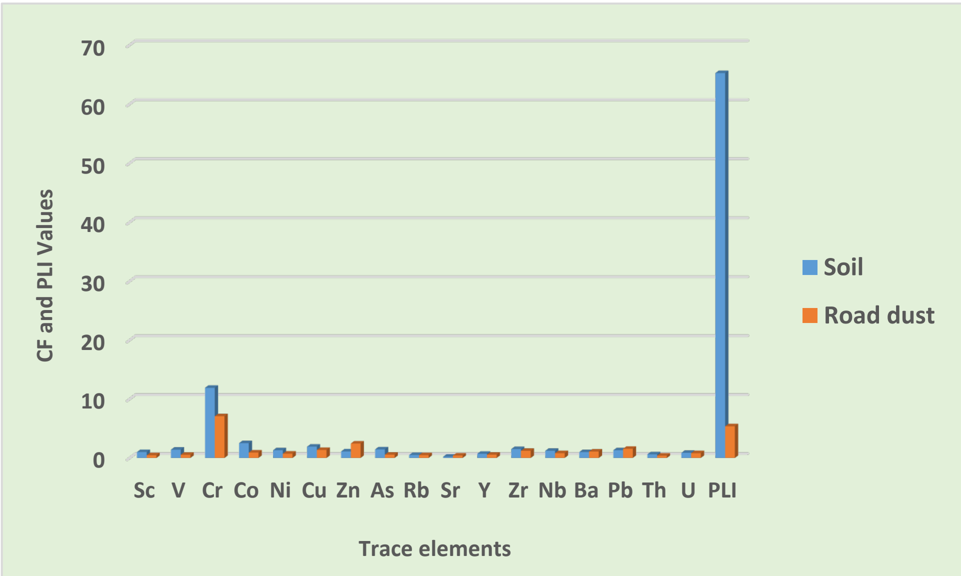

Figure 5.7 Contamination factor and pollution load index of individual trace elements in soil and road dust

5.4.5 Pollution load index

The outcomes of the PLI for all the identified trace elements in soil ranged from 0.23 to 3 520.8, with a mean concentration of 65.24, as presented in Table 5.11, whereas in road dust it ranged between 0.68 and 72.9, with a mean concentration of 5.37 (Table 5.12). According to the PLI classifications, the soil and road dust of Winnie Mandela informal settlement were very highly polluted, which is similar to the study conducted in soil of the Kumasi Metropolis in Ghana (Akoto et al. 2017) and in the street dust of Ho Chi Minh City in Vietnam (Dat et al. 2021). Unlike the findings of this study, the soil of Dhaka in Bangladesh were reported to be strongly contaminated (Ahmed et al. 2016), Fallujah in Iraq lowly polluted (Salah et al. 2013), and Kumasi Metropolis in Ghana lowly polluted (Konwuruk et al. 2021). This shows a difference in pollution level of heavy metals in Winnie Mandela informal settlement and other global urban cities.

High PLI results in soil and road dust signify that man-made activities such as poor waste management, unregulated waste incineration, sewage waste, coal fly ashes, and unplanned construction have a high influence in trace element concentrations. Furthermore, daily heavy traffic within the study area may also be a major contributor to the high levels of trace elements. According to Adamiec (2017), Candeias et al. (2020), Dehghani et al. (2017), Moryani et al. (2020), Sager (2020), Shi et al. (2017) and Victoria et al. (2014), traffic has the potential to increase heavy metal concentrations through vehicle exhaust fumes, tyre rubber, tyre abrasion, corrosion of vehicle parts, wearing of brake pads, gasoline, road paint, and oil combustion.

Furthermore, the PLI in soil was shockingly high when compared to those in road dust (Figure 5.7). These outcomes revealed that Winnie Mandela informal settlement was polluted by heavy metals that can lead to population becoming a high risk. Considering that soil pollution because of heavy metals was astonishing high when compared to that of road dust, children may be at high risk of exposure to heavy metals due to their playing habits or by sucking their hands or fingers. Therefore, remediation and regular monitoring is of paramount importance.

5.4.6 Enrichment factor

The EF values of trace elements in soil and road dust were calculated using Equation 4, described in Chapter 4. The average shale values were used as the background concentration and scandium (Sc) was chosen as a reference metal. The EF mean values of all the trace elements in soil and road dust are presented in Table 5.13 and Table 5.14, respectively. The EF mean values in soil were as follows: Cr (11.9), Co (2.4), Cu (1.9), Zr (1.48), As (1.45), V (1.4), Pb (1.28), Ni (1.26), Nb (1.15), Zn (1.1), Sc (1), Ba (0.99), U (0.86), Y (0.67), Th (0.62), Rb (0.5) and Sr (0.21), whereas in road dust as Cr (7.08), Zn (2.44), Pb (1.54), Cu (1.35), Zr (1.2), Ba (1.08), Sc (1), Co (0.92), U (0.78), Nb (0.78), Ni (0.72), Y (0.55), As (0.55), V (0.53), Rb (0.5), Sr (0.4) and Th (0.3).

Table 5.13 Enrichment factor values of trace elements in soil of Winnie Mandela informal settlement

Elements	Enrichment factor mean values	Enrichment category
Cr	11.9	Significant enrichment
Co	2.4	Moderate enrichment
Cu	1.9	Minimal enrichment
Zr	1.48	Minimal enrichment
As	1.45	Minimal enrichment
V	1.4	Minimal enrichment
Pb	1.28	Minimal enrichment
Ni	1.26	Minimal enrichment
Nb	1.15	Minimal enrichment
Zn	1.1	Minimal enrichment
Sc	1	Minimal enrichment
Ba	0.99	Minimal enrichment
U	0.86	Minimal enrichment
Y	0.67	Minimal enrichment
Th	0.62	Minimal enrichment
Rb	0.5	Minimal enrichment
Sr	0.21	Minimal enrichment

Table 5.14 Enrichment factor values of trace elements in road dust of Winnie Mandela informal settlement

Elements	Enrichment factor mean values	Enrichment category
Cr	7.08	Significant enrichment
Zn	2.44	Moderate enrichment
Pb	1.54	Minimal enrichment
Cu	1.35	Minimal enrichment
Zr	1.2	Minimal enrichment
Ba	1.08	Minimal enrichment
Sc	1	Minimal enrichment
Co	0.92	Minimal enrichment
U	0.78	Minimal enrichment
Nb	0.78	Minimal enrichment
Ni	0.72	Minimal enrichment
Y	0.55	Minimal enrichment
As	0.55	Minimal enrichment
V	0.53	Minimal enrichment
Rb	0.5	Minimal enrichment
Sr	0.4	Minimal enrichment
Th	0.38	Minimal enrichment

The EF mean values in soil categorised trace elements in three distinct classes of pollution enrichment, namely significant enrichment, moderate enrichment and minimal enrichment. Only Cr (11.9) was between 5 and 20 (EF = 5–20), showing a significant enrichment possibly from anthropogenic activities. This is unlike the findings of the study conducted by Odat (2013) in Jordan along the Irbid–Zarqa highway, which reported Cr to be of minimal enrichment. In the study in Fallujah City, Iraq, Salah et al. (2013) observed very highly enriched soil by Cr. Moderate enrichment (EF = 2–5) was reported for Co (2.4), indicating a slight influence of Co through man-made activities, which is in agreement with the study conducted in roadside soil of the Irbid–Zarqa highway in Jordan (Odat 2013). Other trace elements such as Cu, Zr, As, V, Pb, Ni, Nb, Zn, Sc, Ba, U, Y, Th, Rb and Sr were of minimal enrichment (EF < 2), signifying a natural origin. This is comparable to the findings of the study in Botswana (Mmolawa et al. 2011), which reported soil along the major roadside to be minimally enriched by Cu, Ni, Pb and Zn; and in the Kumasi Metropolis, Ghana (Konwuruk et al. 2021), which observed minimal enrichment of As, Pb, Cu, Ni, Zn and V in peri-urban topsoil, and in

Dhaka city, Bangladesh (Rahman et al 2021), which witnessed minimal enrichment of soil by Sr, Zn, Rb, Cu and Pb. The influence of anthropogenic activities in trace element enrichment in soil of Winnie Mandela informal settlements was better as compared to soil of Fallujah City, Iraq (Salah et al. 2013), which exhibited extreme enrichment of Co, very high enrichment of Cr, Ni, Pb, Cu and significant enrichment of Zn.

Moreover, the EF mean values for Cr (7.08) in road dust was also between 5 and 20 (EF = 5–20), showing significant enrichment possibly from human activities that matched the findings of the study conducted in road dust of Katowice and Wroclaw, Poland (Rybak et al. 2020), and surpassed those observed by Cai and Li (2019) in street dust of Shijiazhuang, China, who reported Cr to be of minimal enrichment. Moderate enrichment (EF = 2–5) was reported for Zn (2.44), indicating anthropogenic sources that is better than the study conducted in Lagos metropolis, Nigeria (Taiwo et al. 2020), which observed very high enrichment of Zn. Other trace elements Pb, Cu, Zr, Ba, Sc, Co, U, Nb, Ni, Y, As, V, Rb, Sr and Th were classified as minimal enrichment (EF < 2), signifying a natural origin. This agrees with the studies conducted on road dust of Dhaka city, Bangladesh (Khan et al. 2018), which reported Pb and As to be of minimal enrichment; road dust of Bolgatanga Municipality, Ghana (Victoria et al. 2014), which classified Cu, Zn, Pb, Ni, As and Co as minimal enrichment; in Dhaka, Bangladesh (Kabir et al. 2019), which revealed Co to be of minimal enrichment and in Lagos metropolis, Nigeria (Taiwo et al. 2020), which showed minimal enrichment of Ni.

It is worth noting that the differences in soil and road dust enrichment factor values may be influenced by various factors within a particular area of study. Factors such as the geology of the area, development of the area or the type of human activities within a particular area of study may influence heavy metal enrichment in both soil and road dust. The selection of reference materials in calculating EF, such as average shale values (preferred in this study), crustal earth values or local background values may also have an impact on EF values. Furthermore, the selection of an element of reference (Sc in this study) which normally differs from one study to another, may have an influence in the results of EF (Mmolawa et al. 2011; Victoria et al. 2014).

The findings of the enrichment factor average values in soil and road dust were decreasing as follows Cr > Co > Cu > Zr > As > V > Pb > Ni > Nb > Zn > Sc > Ba > U > Y > Th > R > Sr and Cr > Zn > Pb > Cu > Zr > Ba > Sc > Co > U > Nb > Ni > Y > As > V > Rb > Sr > Th, respectively. Cr was the major contributor to the enrichment of pollution in both soil and road dust, indicating that the influence of anthropogenic activities was high in soil. It was followed by Co and Zn in soil and road dust, respectively. In comparison, Cr in soil was higher than Cr in road dust (Figure 5.8).

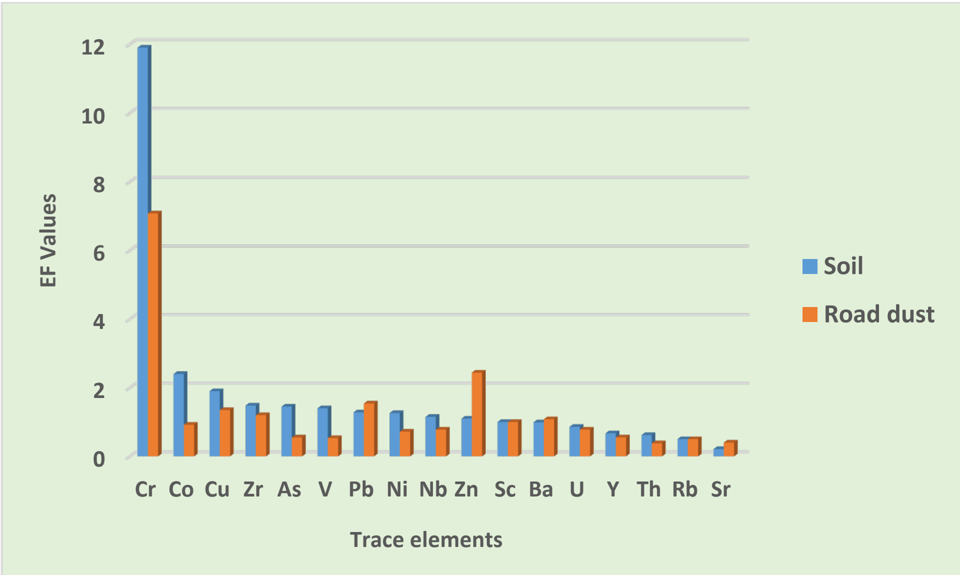

Figure 5.8 Enrichment factor values of trace elements in soil and road dust

The anthropogenic source of Cr, Co and Zn in this informal settlement may be related to traffic and human activities such as waste incineration, poor waste management and sewage waste. Various authors agreed that waste incineration, poor waste management and sewage waste may elevate the concentration of heavy metals in an urban environment. According to Hassaan et al. (2016), sewage and incineration of plastic waste may release Zn into urban areas. Street painting is regarded as a source of Co (Hassaan et al. 2016; Shi et al. 2017), whereas corrosion of vehicle parts may release Cr in urban areas (Victoria et al. 2014). Other trace elements in both soil and road dust were of crustal origin, except Cu and Pb in soil and road dust, respectively, which were slightly influenced by human activities. The natural source of these trace elements can be attributed to the geology of the area, precipitation, or wind-borne soil particles (Maeaba et al. 2019). From the results of EF, it can be confirmed that Cr was an element of public concern in both soil and road dust, which agrees with the results of geo-accumulation and contamination factors. Therefore, the high level of Cr in soil and road dust of Winnie Mandela informal settlement should be given serious attention.

5.5 Health risk assessment of trace elements in soil and road dust

The health risk assessment of trace element contaminants in soil and road dust through various exposure pathways was evaluated by calculating both non-carcinogenic and carcinogenic risks for the population (children and adults) of Winnie Mandela informal settlement. This was done by Equations 5 to 13, described in Chapter 4. Reference doses (RfD) and slope factors (SF) as presented in Table 5.15, were used for noncarcinogenic and carcinogenic risk assessments, respectively. The overall health risk assessment of trace elements in this study did not take into account the size of road dust particles; thus, it used the dust content as the inhalation amount to make an overall estimation of the health risk assessment. Therefore, the findings of this study represent the most probable manifestation of health risks, which also offer data worth for risk warning, controlling and avoiding contamination.

Table 5.15 Reference doses for noncarcinogenic risk assessment and slope factors for carcinogenic risk assessment

Elements	Reference doses (RfD) (mg/kg/d)			Slope factors (SF) (mg/kg/d)			References
	RfD_{ing}	RfD_{inh}	RfD_{derm}	SF_{ing}	SF_{inh}	SF_{derm}	
Sc	–	–	–	–	–	–	–
V	7.00E-03	7.00E-03	7.00E-03	–	–	–	[Tan et al. 2021]
Cr	3.00E-03	2.86E-06	6.00E-05	5.00E-01	4.10E-01	–	[Gabarrón et al. 2017; Tan et al. 2021]
Co	2.00E-02	2.00E-02	5.40E-03	–	8.40E-01	–	[Gabarrón et al. 2017]
Ni	2.00E-02	6.00E-06	1.60E-02	9.10E-01	9.80E+00	–	[Gabarrón et al. 2017]
Cu	4.00E-02	4.00E-02	1.20E-02	–	–	–	[Gabarrón et al. 2017]
Zn	3.00E-01	3.00E-01	6.00E-02	–	–	-	[Gabarrón et al. 2017]
As	3.00E-04	3.00E-04	1.20E-04	1.50E+00	1.51E+01	3.66E+00	[Kamunda et al. 2016; Tan et al. 2021]
Rb	–	–	–	–	–	–	–
Sr	6.00E-01	–	1.20E-01	–	–	-	[Ferreira and De Miguel 2005]
Y	–	–	–	–	–	–	–
Zr	–	–	–	–	–	–	–
Nb	–	–	–	–	–	–	–
Ba	7.00E-02	1.43E-04	4.90E-03	–	–	–	[Ferreira and De Miguel 2005]
Pb	3.50E-03	3.50E-03	5.25E-04	8.50E-03	4.20E-02	-	[Gabarrón et al. 2017; Kamunda et al. 2016]
Th	–	–	–	–	–	–	–
U	6.00E-01	–	5.10E-04	–	–	–	[Ferreira and De Miguel 2005]

5.5.1 Noncarcinogenic risk assessment

The noncarcinogenic risk values computed for soil and road dust were based on the ADD values summarised in Table 5.16 and on RfD in Table 5.15. The average daily doses for noncarcinogenic risk assessment of Sc, V, Cr, Co, Ni, Cu, Zn, As, Rb, Sr, Y, Zr, Nb, Ba, Pb, Th and U were computed centred on three exposure pathways (ADD_{ing}, ADD_{inh}, and ADD_{derm}) for soil and road dust. Their average values are presented in Table 5.16 and Table 5.18, respectively. Furthermore, the average daily doses were used to assess the noncarcinogenic risks of heavy metals in soil and road dust for both children and adults. The results are summarised in Table 5.17 and Table 5.19 for soil and road dust, respectively, as hazard quotient (HQ) and hazard index (HI) for ingestion, inhalation and dermal pathways. Noncarcinogenic risks for trace elements such as Sc, Rb, Sr, Y, Zr, Nb and Th were not assessed due to lack of their slope factors.

The outcomes of the noncarcinogenic risk assessment in soil revealed that the total noncarcinogenic risks (THI) in children was 8.16E+00, mostly contributed by the ingestion pathway (6.02E+00). It was followed by dermal contact (2.04E+00) and inhalation pathways (9.50E-02). The contribution of individual elements to noncarcinogenic risk value was as Cr (6.75E+00), As (8.18E-01), V (3.33E-01), Ba (1.18E-01), Ni (5.41E-02), Co (3.10E-02), Cu (3.08E-02), Pb (1.37E-02), Zn (4.32E-03), Sr (1.38E-03) and U (7.85E-04). In adults, the THI value was 2.56E+00, driven mostly by dermal contact (1.56E+00), followed by ingestion (8.58E-01) and inhalation pathway (1.35E-01). The values of noncarcinogenic risk in adults was contributed by individual elements as Cr (2.30E+00), As (1.23E-01), V (4.65E-02), Ni (4.52E-02), Ba (2.43E-02), Pb (8.64E-03), Co (4.74E-03), Cu (4.61E-03), Zn (7.49E-04), U (5.44E-04) and Sr (2.27E-04).

The HI is regarded as the total sum of the HQ. It is an important factor used to measure the noncarcinogenic risks of heavy metals (Kamunda et al. 2016). The HI value of greater than one specifies the likelihood of noncarcinogenic risk, whereas the HI value of less than one specifies no probability of noncarcinogenic risk (USEPA 2004). In this study, the calculated total HI value for soil in the children population was equal to 8.16E+00, a value greater than one signifying a possibility of noncarcinogenic risk to children of Winnie Mandela informal settlement. The total HI value through ingestion (6.02E+00) and dermal (2.04E+00) pathways were above one, indicating a possibility of noncarcinogenic risk through ingestion and dermal contact. However, the inhalation (9.50E-02) value was less than one, showing no possibility of noncarcinogenic risk. The total HI value through various exposure pathways was trending as ingestion > dermal > inhalation. The HI values of all the elements exhibited values that were less than one, signifying no likelihood of noncarcinogenic risk, except Cr with a value of 6.75E+00, showing the possibility of noncarcinogenic risk and their ranking were as Cr > As > V > Ba > Ni > Co > Cu > Pb > Zn > Sr > U.

These findings are in agreement with the discoveries of the study conducted on soil of Dongguan, China, by Liu et al. (2016), who reported the Cr value to be above one. Furthermore, in soil of Dongguan, China (Liu et al. 2016), Mongolian major cities (Chonokhuu et al. 2019), Ijebu-Ode, Nigeria (Adedeji et al. 2019), Perlis state, Malaysia (Ahmad et al. 2021), Lagos state, Nigeria (Olatunde et al. 2018) and Murcia City, Spain (Acosta et al. 2009), ingestion was delineated as the major contributor to noncarcinogenic risk which supports the findings of this study.

In addition, the calculated total HI value for soil in the adult population was 2.56E+00. This value was higher than one, indicating a likelihood of noncarcinogenic risk to the adult population. The total HI value for ingestion (8.58E-01) and inhalation (1.35E-01) were less than one, indicating no chance of noncarcinogenic risk via these pathways. However, dermal contact (1.56E+00) was greater than one, which is a clear indication of a possibility of noncarcinogenic risk. The total HI values through various exposure pathways were trending orderly as dermal > ingestion > inhalation. Among all the heavy metals, only Cr with a value of 2.30E+00 was the major contributor to noncarcinogenic risk and exhibited a possibility of noncarcinogenic risk. The contributions of individual trace elements to the total hazard index value were descending as Cr > As > V > Ni > Ba > Pb > Co > Cu > Zn > U > Sr. These findings are comparable to the findings of Adedeji et al. (2019) in soil of Ijebu-Ode, Nigeria, which showed dermal contact as the leading contributor to noncarcinogenic risk in the adult population. Unlike the findings of this study, in Mongolian major cities (Chonokhuu et al. 2019) and Perlis state, Malaysia (Ahmad et al. 2021), ingestion was reported as the main contributor to noncarcinogenic risk in the adult population.

Moreover, the THI value in children was higher than the THI value in the adult population, proving a higher possibility of heavy metals to cause noncarcinogenic risk in children than in the adult population (Figure 5.9), which correlates very well with the results of Chonokhuu et al. (2019) and Adedeji et al. (2019). Ingestion was the main contributor to noncarcinogenic risk in children, whereas in the adult population dermal contact was the main contributor to noncarcinogenic risk. Therefore, the high noncarcinogenic risk in children through ingestion cannot be ignored as children have the tendency of sucking their hands or fingers (Liu et al. 2016). As illustrated in Figure 5.10, Cr was the leading contributor to noncarcinogenic risk in both children and adults. As a result, the children population of Winnie Mandela informal settlement were confronted with the possibility of noncarcinogenic risk as a result of Cr exposure, mainly through ingestion. For the adult population, noncarcinogenic risk as a result of Cr exposure was mainly via dermal contact.

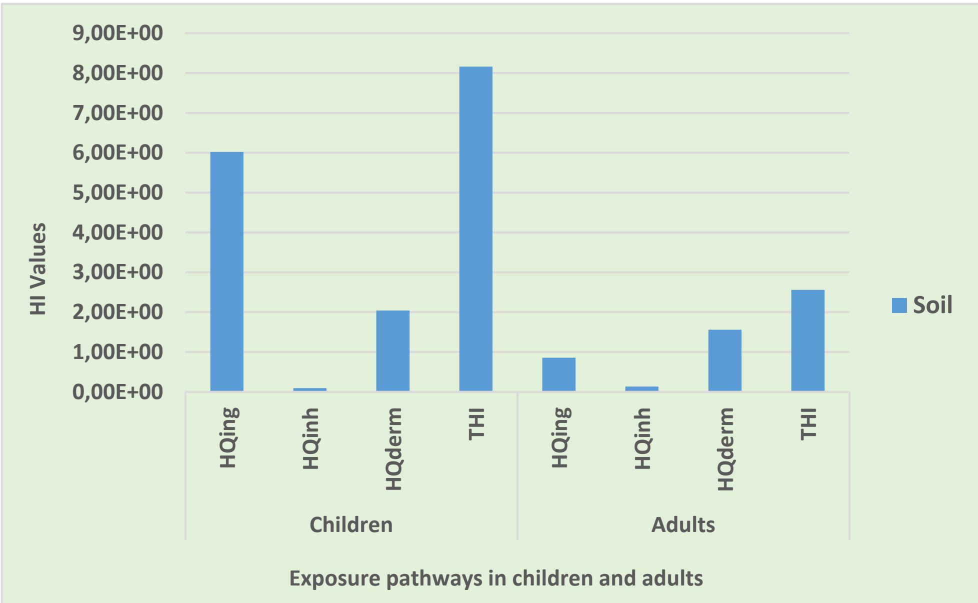

Figure 5.9 Hazard index for trace element exposure via various pathways in soil

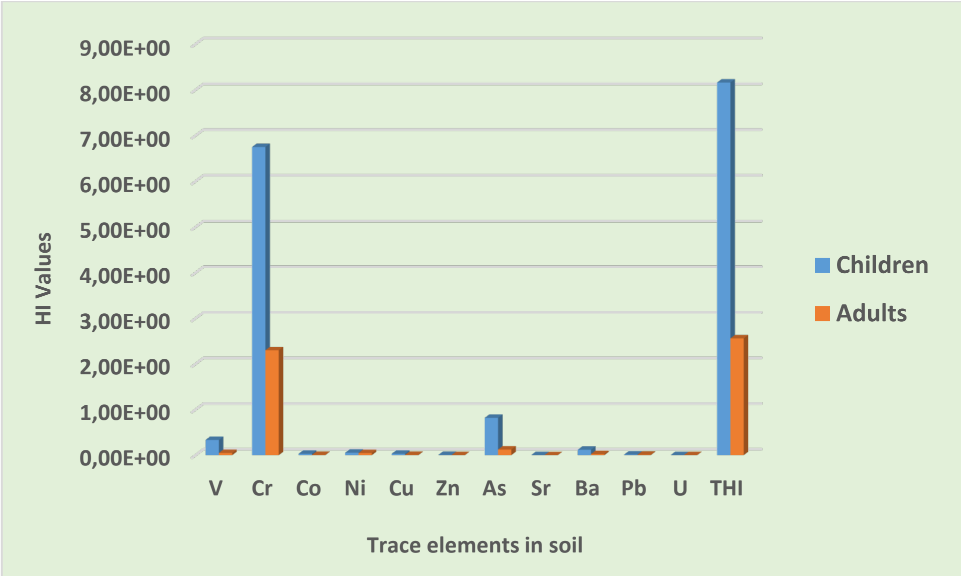

Figure 5.10 Contribution of individual trace elements in soil to noncarcinogenic risk in children and adults

Furthermore, the findings of this study showed that trace elements in soil have the possibility to contribute to noncarcinogenic risks, which is similar to the findings observed by Liu et al. (2016) in the soils of Dongguan, China, which reported the possibility of soil to cause noncarcinogenic risk. To the contrary, the soils of Mongolian major cities (Chonokhuu et al. 2019), Ijebu-Ode, Nigeria (Adedeji et al. 2019) and Perlis state, Malaysia (Ahmad et al. 2021) showed no possibility to cause noncarcinogenic risk to the local inhabitants. As reported in the literature, industrial activities, population density, traffic density, development of the area, geology of the area, climate, sampling and analytical methods may influence the difference in concentration of heavy metals (Ma and Singhirunnusorn 2012; Shi et al. 2017), therefore it can also be concluded that the risk values may also be influenced by these factors. The higher the concentration of the trace elements in an area, the higher the likelihood of its risk to increase.

Table 5.16 Noncarcinogenic average daily dose for trace elements in soil via ingestion, inhalation, and dermal exposure pathways for children and adults

Pathways	Noncarcinogenic average daily dose (ADD) for trace elements in soil (mg/kg/day)																	Total ADD
	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U	
Children																		
ADD_{ing}	1.70E-04	2.30E-03	1.40E-02	5.90E-04	1.00E-03	1.10E-03	1.30E-03	2.40E-04	8.50E-04	7.90E-04	2.20E-04	3.00E-03	1.60E-04	7.30E-03	3.30E-04	9.40E-05	4.10E-05	3.35E-02
ADD_{inh}	3.15E-09	4.33E-08	2.59E-07	1.13E-08	2.08E-08	2.08E-08	2.52E-08	4.55E-09	1.61E-08	1.50E-08	4.21E-09	5.75E-08	3.10E-09	1.40E-07	6.25E-09	1.79E-09	7.70E-10	6.33E-07
ADD_{derm}	1.52E-06	2.00E-05	1.20E-04	5.40E-06	9.90E-06	9.74E-06	1.20E-06	2.16E-06	7.66E-06	7.16E-06	2.00E-06	2.74E-05	1.50E-06	6.60E-05	2.97E-06	8.50E-07	3.66E-07	2.86E-04
ADD	**1.72E-04**	**2.32E-03**	**1.41E-02**	**5.95E-04**	**1.01E-03**	**1.11E-03**	**1.30E-03**	**2.42E-04**	**8.58E-04**	**7.97E-04**	**2.22E-04**	**3.03E-03**	**1.62E-04**	**7.37E-03**	**3.33E-04**	**9.49E-05**	**4.14E-05**	**3.38E-02**
Adults																		
ADD_{ing}	2.20E-05	3.00E-04	2.00E-03	8.00E-05	1.50E-03	1.50E-03	1.80E-04	3.20E-05	1.10E-04	1.10E-04	2.90E-05	4.10E-04	2.20E-05	9.30E-04	4.40E-05	1.30E-05	5.40E-06	7.29E-03
ADD_{inh}	3.38E-09	4.65E-08	2.78E-07	1.22E-08	2.23E-07	2.23E-08	2.71E-08	4.89E-09	1.73E-08	1.62E-08	4.52E-09	6.20E-08	3.33E-09	1.49E-07	6.70E-09	1.92E-09	8.30E-09	8.87E-07
ADD_{derm}	1.12E-06	1.53E-05	9.18E-05	4.01E-06	7.40E-06	7.35E-06	8.94E-06	1.61E-06	5.71E-06	5.33E-06	1.50E-06	2.04E-05	1.09E-06	4.92E-05	2.21E-06	6.33E-07	2.73E-07	2.24E-04
ADD	**2.31E-05**	**3.15E-04**	**2.09E-03**	**8.40E-05**	**1.51E-03**	**1.51E-03**	**1.89E-04**	**3.36E-05**	**1.16E-04**	**1.15E-04**	**3.05E-05**	**4.30E-04**	**2.31E-05**	**9.79E-04**	**4.62E-05**	**1.36E-05**	**5.68E-06**	**7.51E-03**

Table 5.17 Noncarcinogenic risk values (hazard quotient and hazard index) for trace elements in soil via ingestion, inhalation, and dermal exposure pathways for children and adults

Pathways	Noncarcinogenic risk values (hazard quotient [HQ] and hazard index [HI]) for trace elements in soil (mg/kg/day)																Total HI
	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U	
Children																		
HQ_{ing}	–	3.30E-01	4.66E+00	3.00E-02	5.00E-02	3.00E-02	4.30E-03	8.00E-01	–	1.32E-03	–	–	–	1.04E-01	8.08E-03	–	6.83E-05	6.02E+00
HQ_{inh}	–	6.18E-06	9.05E-02	5.65E-07	3.47E-03	5.20E-07	8.40E-08	1.52E-05	–	–	–	–	–	9.79E-04	1.78E-06	–	–	9.50E-02
HQ_{derm}	–	2.86E-03	2.00E+00	1.00E-03	6.19E-04	8.12E-04	2.00E-05	1.80E-02	–	5.97E-05	–	–	–	1.35E-02	5.66E-03	–	7.17E-04	2.04E+00
HI	–	**3.33E-01**	**6.75E+00**	**3.10E-02**	**5.41E-02**	**3.08E-02**	**4.32E-03**	**8.18E-01**	–	**1.38E-03**	–	–	–	**1.18E-01**	**1.37E-02**	–	**7.85E-04**	**8.16E+00**
Adults																		
HQ_{ing}	–	4.43E-02	6.70E-01	4.00E-03	7.50E-03	4.00E-03	6.00E-04	1.10E-01	–	1.83E-04	–	–	–	1.33E-02	4.43E-03	–	9.00E-06	8.58E-01
HQ_{inh}	–	6.64E-06	9.72E-02	6.10E-07	3.72E-02	5.57E-07	9.03E-08	1.63E-05	–	–	–	–	–	1.04E-03	1.91E-06	–	–	1.35E-01
HQ_{derm}	–	2.18E-03	1.53E+00	7.42E-04	4.62E-04	6.12E-04	1.49E-04	1.34E-02	–	4.44E-05	–	–	–	1.00E-02	4.21E-03	–	5.35E-04	1.56E+00
HI	–	**4.65E-02**	**2.30E+00**	**4.74E-03**	**4.52E-02**	**4.61E-03**	**7.49E-04**	**1.23E-01**	–	**2.27E-04**	–	–	–	**2.43E-02**	**8.64E-03**	–	**5.44E-04**	**2.56E+00**

The results of noncarcinogenic risks in road dust are summarised in Table 5.19. The total noncarcinogenic risk (THI) in children was 4.74E+00, mainly contributed by the ingestion pathway (3.43E+00). It was followed by dermal contact (1.25E+00) and the inhalation pathway (5.69E-00). Individual trace elements contributed to the total noncarcinogenic risk as Cr (3.97E+00), As (3.13E-01), Ba (1.30E-01), V (1.27E-01), Pb (1.18E-01), Ni (3.39E-02), Cu (2.01E-02), Co (1.14E-02), Zn (1.01E-02), Sr (2.55E-03) and U (7.17E-04). In adults, the THI value was 1.47E+00. It was contributed mostly by dermal contact (9.41E-01), followed by the ingestion pathway (4.68E-01) and inhalation pathway (6.13E-02). The value of the total noncarcinogenic risk was contributed by individual elements: Cr (1.34E+00), As (4.61E-02), Ba (2.74E-02), Pb (2.01E-02), V (1.79E-02), Ni (6.63E-03), Sr (3.52E-03), Cu (2.94E-03), Co (1.77E-03), Zn (1.66E-03) and U (4.94E-04).

The assessment of noncarcinogenic risk in road dust showed the total HI value in the children population to be 4.74E+00. The THI value was greater than one, connoting a possibility of noncarcinogenic risk to the children of Winnie Mandela informal settlement. It was driven greatly by ingestion (3.43E+00), followed by the dermal contact pathway (1.25E+00), with values greater than one specifying the possibility of noncarcinogenic risk via ingestion and dermal contact. Inhalation pathways with a value of 5.69E-02, which was below one, signalled that there may be no possibility of noncarcinogenic through inhalation in the children population. The total HI values through various exposure pathways were descending as ingestion > dermal > inhalation. These findings suggested the possibility of noncarcinogenic risk among the children group, mainly through ingestion. The HI values of all elements showed values that were less than one, demonstrating no likelihood of noncarcinogenic risk, except Cr with a value of 3.97E+00, displaying the possibility of noncarcinogenic risk from its exposure. Their individual contributions to the total HI value were Cr > As > Ba > V > Pb > Ni > Cu > Co > Zn > Sr > U.

The discoveries of this study are similar to the findings of the studies conducted in road dust of Viano do Castelo, Portugal (Candeais et al. 2020), Wroclaw and Katowice, Poland (Rybak et al. 2020), the urbanised cities of Pakistan (Qadeer et al. 2020), the Maha Sarakham municipality, Thailand (Ma and Singhirunnusorn 2012), Xi'an, China (Shi et al. 2017), Lagos metropolis, Nigeria (Taiwo et al. 2020), Luanda, Angola (Ferreira-Baptista and De Miguel 2005), Xi'an Ancient City Wall, China (Li et al. 2019), Alexandria and Kafr El-Sheikh, Egypt (Jadoon et al. 2020), which point out that ingestion in the children group is the principal contributor to noncarcinogenic risk. Furthermore, several researchers (Li et al. 2019; Taiwo et al. 2017, 2020) reported Cr as the principal contributor to noncarcinogenic risk in road dust, which supports the findings of this study.

Moreover, in the adult population, the total HI value in road dust was reported to be 1.47E+00. This value was higher than one, showing the likelihood to cause noncarcinogenic risks among the adult population. It was mainly contributed by dermal contact (9.41E-00), followed by the ingestion (4.68E-01) and inhalation (6.13E-02) pathways. The total HI values for each of the exposure pathways were less than one, indicating no chance of noncarcinogenic risk via these exposure pathways in the adult population. The trend of exposure pathways was dermal > ingestion > inhalation, which showed the possibility of noncarcinogenic effects through dermal contact in the adult population. The possibility of noncarcinogenic risk among the adult population was mainly influenced by Cr with a value of 1.34E+00. The HI value of all the other elements were less than one, signifying no chance of noncarcinogenic risk and their contributions to the total hazard index was as Cr > As > Ba > Pb > V > Ni > Sr > Cu > Co > Zn > U. Many previous studies on road dust reported ingestion as the leading contributor to noncarcinogenic in the adult population (Candeais et al. 2020; Ferreira-Baptista and De Miguel 2005; Ma and Singhirunnusorn 2012; Qadeer et al. 2020; Rybak et al. 2020; Shi et al. 2017; Taiwo et al. 2020). which is unlike the findings of this study that revealed dermal contact as the leading contributor to noncarcinogenic risk.

In addition, the total HI value in the children population was higher than the total HI value in the adult population, demonstrating the high possibility of heavy metals to cause noncarcinogenic risk to children than in the adult population (Figure 5.11), which is similar to the findings of Candeias et al. (2020), Chen et al. *(*2017), Li et al. (2019), Qadeer et al. (2020), Shi et al. *(*2017), Tan et al. (2021), Taiwo et al. (2020) and Zheng et al. (2010a). In the children population, ingestion was the main contributor to noncarcinogenic risk, which is a concern as children have the custom of sucking their fingers or hands (Liu et al. 2016). In adults, dermal contact was the major contributor to noncarcinogenic risk which makes resuspended particles a serious concern (Candeias et al. 2020). As shown in Figure 5.12, Cr was the main driver to noncarcinogenic risk in the population of Winnie Mandela informal settlement. Consequently, the children population were faced with the probability of noncarcinogenic risk as a result of Cr exposure mainly through ingestion. For the adult population, noncarcinogenic risk as a result of Cr exposure was possible through dermal contact, although this exposure pathway showed a value of less than one. However, long-term exposure to high concentrations of Cr through this exposure route may cause noncarcinogenic risk.

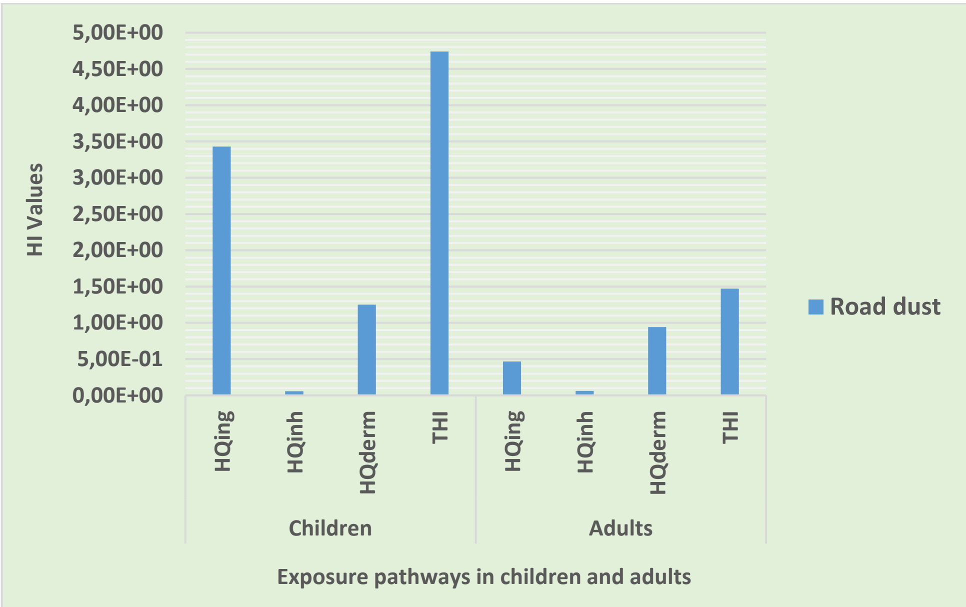

Figure 5.11 Hazard index of trace element exposure via various pathways in road dust

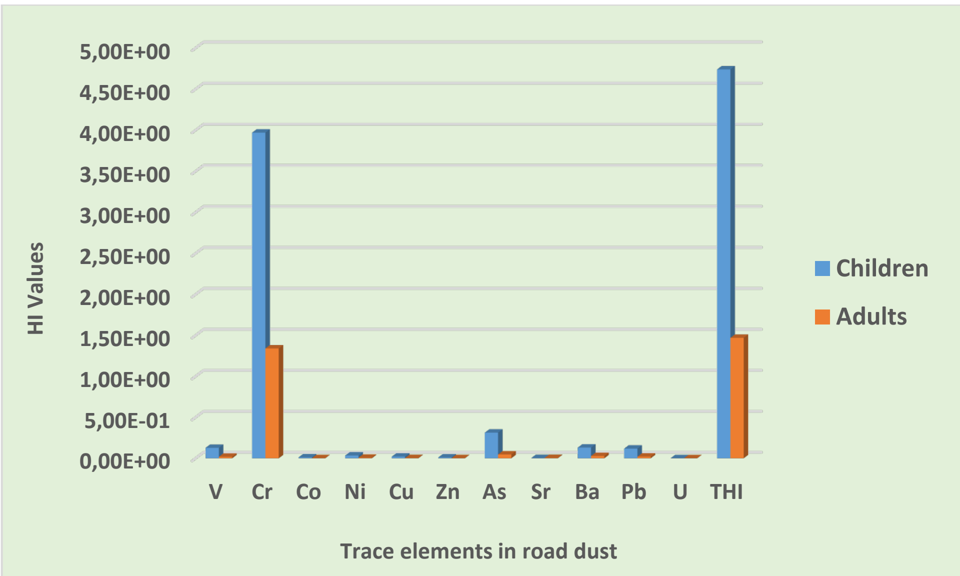

Figure 5.12 Contribution of individual trace elements in road dust to noncarcinogenic risk in children and adults

Moreover, the trace elements in road dust have the possibility to contribute to noncarcinogenic risks for all the population groups as their total HI values were greater than one, which agrees with the study conducted in Viano do Castelo, Portugal (Candeias et al. 2020), Tianshui, China (Tan et al. 2021), and Lagos metropolis, Nigeria (Taiwo et al. 2020). Other studies conducted on road dust were that of Wroclaw and Katowice, Poland (Rybak et al. 2020), urbanised cities of Pakistan (Qadeer et al. 2020), the Maha Sarakham municipality, Thailand (Ma and Singhirunnusorn 2012), Xi'an, China (Shi et al. 2017) and Xi'an Ancient City Wall, China (Li et al. 2019), which revealed that trace elements in road dust have a low noncarcinogenic risk to the surrounding population. This is different from the findings of this study indicating a high noncarcinogenic risk to the inhabitants of Winnie Mandela informal settlement than these urban city populations.

Table 5.18 Noncarcinogenic average daily dose for trace elements in road dust via ingestion, inhalation, and dermal exposure pathways for children and adults

Pathways	Noncarcinogenic average daily dose (ADD) for trace elements in road dust (mg/kg/day)																	Total ADD
	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U	
Children																		
ADD_{ing}	7.43E-05	8.80E-04	8.10E-03	2.20E-04	6.30E-04	7.80E-04	2.90E-03	9.20E-05	8.43E-04	1.53E-03	1.84E-04	2.43E-03	1.11E-04	8.00E-03	3.90E-04	5.85E-05	3.70E-05	2.73E-02
ADD_{inh}	1.40E-09	1.70E-08	1.54E-07	4.21E-09	1.20E-08	1.50E-08	5.61E-08	1.74E-09	1.60E-08	2.91E-08	3.50E-09	4.60E-08	2.08E-09	1.51E-07	7.46E-09	1.10E-09	7.02E-10	5.18E-07
ADD_{derm}	6.67E-09	7.94E-06	7.33E-05	2.00E-06	5.64E-06	7.02E-06	2.67E-05	8.30E-07	7.59E-06	1.40E-05	1.66E-06	2.20E-06	9.90E-07	7.20E-05	3.54E-06	5.27E-07	3.34E-07	2.26E-04
ADD	**7.43E-05**	**8.88E-04**	**8.17E-03**	**2.22E-04**	**6.36E-04**	**7.87E-04**	**2.93E-03**	**9.28E-05**	**8.51E-04**	**1.54E-03**	**1.86E-04**	**2.43E-03**	**1.12E-04**	**8.07E-03**	**3.94E-04**	**5.90E-05**	**3.73E-05**	**2.75E-02**
Adults																		
ADD_{ing}	9.94E-06	1.20E-04	1.10E-03	2.98E-05	8.40E-05	1.00E-04	4.00E-04	1.23E-05	1.13E-04	2.06E-04	2.47E-05	3.26E-04	1.47E-05	1.07E-03	5.28E-05	7.86E-06	4.97E-06	3.68E-03
ADD_{inh}	1.50E-09	1.80E-08	1.66E-07	4.52E-09	1.30E-08	1.60E-08	6.02E-08	1.90E-09	1.71E-08	3.12E-08	3.74E-09	4.94E-08	2.23E-09	1.62E-07	8.00E-09	1.20E-09	7.54E-10	5.57E-07
ADD_{derm}	4.97E-07	5.92E-06	5.50E-05	1.49E-06	4.20E-06	5.23E-06	1.99E-05	6.17E-07	5.66E-06	1.03E-05	1.23E-06	1.63E-05	7.40E-07	5.40E-05	2.64E-06	3.93E-07	2.49E-07	1.84E-04
ADD	**1.04E-05**	**1.26E-04**	**1.16E-03**	**3.13E-05**	**8.82E-05**	**1.05E-04**	**4.20E-04**	**1.29E-05**	**1.19E-04**	**2.16E-04**	**2.59E-05**	**3.42E-04**	**1.54E-05**	**1.12E-03**	**5.54E-05**	**8.25E-06**	**5.22E-06**	**3.86E-03**

Table 5.19 Noncarcinogenic risk (hazard index and hazard) values for trace elements in road dust via ingestion, inhalation, and dermal exposure pathways for children and adult

Pathways	Noncarcinogenic risk (hazard quotient [HQ] and hazard index [HI]) and values for trace elements in road dust (mg/kg/day)																	Total HI
	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U	
Children																		
HQ_{ing}	–	1.26E-01	2.70E+00	1.10E-02	3.15E-02	1.95E-02	9.67E-03	3.06E-01	–	2.55E-03	–	–	–	1.14E-01	1.11E-01	–	6.17E-05	3.43E+00
HQ_{inh}	–	2.43E-06	5.38E-02	2.10E-07	2.00E-03	3.75E-07	1.87E-07	5.80E-06	–	-	–	–	–	1.05E-03	2.13E-06	–	-	5.69E-02
HQ_{derm}	–	1.13E-03	1.22E+00	3.70E-04	3.52E-04	5.85E-04	4.45E-04	6.92E-03	–	-	–	–	–	1.47E-02	6.74E-03	–	6.55E-04	1.25E+00
HI	–	**1.27E-01**	**3.97E+00**	**1.14E-02**	**3.39E-02**	**2.01E-02**	**1.01E-02**	**3.13E-01**	–	**2.55E-03**	–	–	–	**1.30E-01**	**1.18E-01**	–	**7.17E-04**	**4.74E+00**
Adults																		
HQ_{ing}	–	1.71E-02	3.67E-01	1.49E-03	4.20E-03	2.50E-03	1.33E-03	4.10E-02	–	3.43E-03	-	–	–	1.53E-02	1.51E-02	–	8.28E-06	4.68E-01
HQ_{inh}	–	2.57E-06	5.80E-02	2.26E-07	2.17E-03	4.00E-07	2.01E-07	6.33E-06	–	-	–	–	–	1.13E-03	2.28E-06	–	-	6.13E-02
HQ_{derm}	–	8.46E-04	9.17E-01	2.76E-04	2.62E-04	4.36E-04	3.32E-04	5.14E-03	–	8.58E-05	–	–	–	1.10E-02	5.03E-03	–	4.88E-04	9.41E-01
HI	–	**1.79E-02**	**1.34E+00**	**1.77E-03**	**6.63E-03**	**2.94E-03**	**1.66E-03**	**4.61E-02**	–	**3.52E-03**	–	–	–	**2.74E-02**	**2.01E-02**	–	**4.96E-04**	**1.47E+00**

5.5.2 Carcinogenic risk assessment

The ADD values in Table 5.20 and the slope factors in Table 5-15 were used to assess the carcinogenic risks of Cr, Ni, As, Pb and Co in soil for both children and adults. This was done using Equations 10 to 13 as described in Chapter 4. As a result of the lack of their carcinogenic slope factors, Sc, V, Cu, Zn, Rb, Sr, Y, Zr, Nb, Ba, Th and U carcinogenic risks were not reported in this study. The results are summarised in Table 5.21 as carcinogenic risk and total carcinogenic risk (TCR) for ingestion, inhalation and dermal pathways.

The results of carcinogenic risk in soil exhibited the TCR in children as 7.18E-04 contributed mainly by ingestion (7.17E-04), followed by dermal contact (6.77E-07) and inhalation (3.34E-08) pathways. Individual trace elements contributed to TCR as Cr (6.00E-04), Ni (8.57E-05), As (3.16E-05), Pb (2.40E-07) and Co (8.16E-10). In adult population, the TCR in soil was 3.80E-04. It was mostly contributed by ingestion (3.78E-04) followed by dermal (2.02E-06) and inhalation (1.21E-07). The value of total lifetime carcinogenic risk was contributed by individual element as Cr (3.15E-04), Ni (4.61E-05), As (1.85E-05), Pb (1.30E-07) and Co (3.50E-09).

The permissible carcinogenic risks value endorsed by USEPA, (1989) as cited by Chukwuemeka et al. (2018), is in a range of 10^{-06} to 10^{-04}. The assessment of carcinogenic risks in soil exhibited the TCR value in children as 7.18E-04 higher than the permissible value which was a sign for the possibility of children to develop carcinogenic risk. The ingestion pathway (7.17E-04) was the major driver to carcinogenic risk with a value above the acceptable limit signifying the risk of cancer to children via ingestion. However, the values for dermal contact (6.77E-04) and inhalation (3.34E-08) were within the acceptable value. This indicated that children were not at risk of developing cancer through dermal and inhalation pathways. The TCRs through various exposure pathways were decreasing as ingestion > dermal > inhalation. All the carcinogenic risks values of trace elements were within the acceptable limit showing no possibility of developing cancer, except Cr with a value of 6.00E-04, which has the possibility to cause carcinogenic risk. The carcinogenic risk of all the elements were as Cr > Ni > As > Pb > Co. Similarly, Adimalla (2019) elucidated ingestion in children group as the leading contributor to carcinogenic risk.

Additionally, the adult population TCR in soil was 3.80E-04. This value was higher than the approved value signifying that adults were at risk of cancer. The TCR was mostly contributed by ingestion (3.78E-04) with a value above the satisfactory range indicating the risk of cancer to the adult population through ingestion. Dermal contact and inhalation pathways showed no possibility of cancer risk in the adult population. The contributions of different exposure pathways to carcinogenic risk were ingestion > dermal > inhalation. In the adult population, the Cr carcinogenic risk value (3.14E-04) was the major contributor to carcinogenic risk with a value above the acceptable range. Furthermore, the adults in this study were at risk of developing cancer from Cr mainly via ingestion pathway. The carcinogenic risk values of other heavy metals were within the tolerable limit and their contributions were as Cr > Ni > As > Pb > Co. The outcomes of this study support the findings by Adimalla (2019) which confirmed ingestion as the main contributor to carcinogenic risk in the adult population.

Moreover, the TCR in children group was higher than the TCR in adult group demonstrating that children were at higher risk than adults, Figure 5.13. There is an evidence that children in other urban cities were at high risk when compared to adults (Adedeji et al. 2019; Adimalla 2019). This may be due to children low body mass, behaviours of playing in dust and hand sucking (Jadoon et al. 2020). The ingestion pathway which was a major contributor to carcinogenic risk among the population of this study was higher in children than adult population. Furthermore, as presented in Figure 5.14, Cr as the main driver to carcinogenic risks recorded the highest value in children. These findings clearly demonstrate that the population in this study were confronted with the possibility of carcinogenic risk mainly through ingestion of Cr, particularly in children (the possible health implications of this elements are reported in section 5.6 of this chapter). Furthermore, the level of trace elements in the soil of Winnie Mandela informal settlement showed the possibility to contribute to carcinogenic risks for all the population groups as their TCR values were higher than the permissible value which is in accord with the outcomes of Najmeddin et al. (2018) and Adedeji et al. (2019).

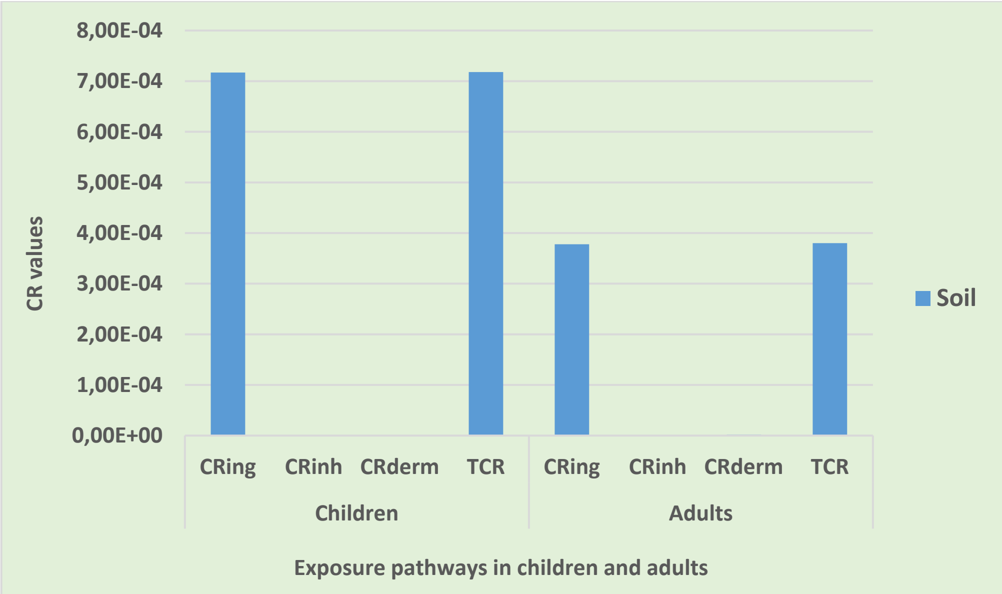

Figure 5.13 Carcinogenic risk of trace elements in soil for children and adults through various exposure routes

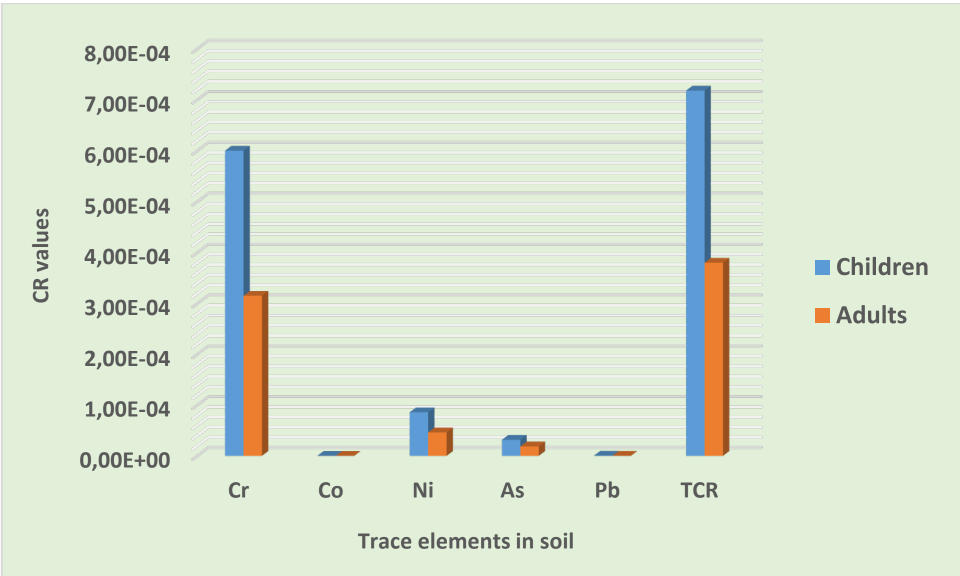

Figure 5.14 Contribution of individual trace elements in soil to carcinogenic risk for children and adult

Table 5.20 Carcinogenic average daily dose for trace elements in soil via ingestion, inhalation, and dermal exposure pathways for children and adults

Pathways	Carcinogenic average daily dose (ADD) for trace elements in soil (mg/kg/day)																	Total ADD
	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U	
Children																		
ADD_{ing}	1.42E-05	2.00E-04	1.20E-03	5.13E-05	9.42E-05	9.40E-05	1.10E-04	2.06E-05	7.30E-05	6.82E-05	1.91E-05	2.60E-04	1.40E-05	6.30E-04	2.83E-05	8.09E-06	4.48E-06	2.89E-03
ADD_{inh}	2.69E-10	3.71E-09	2.22E-08	9.71E-10	1.80E-09	1.78E-09	2.16E-09	3.90E-09	1.38E-09	1.29E-09	3.61E-10	4.93E-09	2.66E-10	1.19E-08	5.33E-10	1.53E-10	6.60E-11	5.77E-08
ADD_{derm}	1.30E-07	1.76E-06	1.05E-05	4.61E-07	8.48E-07	8.46E-07	1.03E-06	1.85E-07	6.57E-07	6.13E-07	1.72E-07	2.34E-06	1.26E-07	5.65E-06	2.54E-07	7.28E-08	3.14E-08	2.57E-05
Total	**1.43E-05**	**2.02E-04**	**1.21E-03**	**5.18E-05**	**9.50E-05**	**9.48E-05**	**1.11E-04**	**2.08E-05**	**7.37E-05**	**6.88E-05**	**1.93E-05**	**2.62E-04**	**1.41E-05**	**6.36E-04**	**2.86E-05**	**8.16E-06**	**4.51E-06**	**2.92E-03**
Adults																		
ADD_{ing}	7.64E-06	1.00E-04	6.30E-04	2.75E-05	5.06E-05	5.05E-05	6.13E-05	1.10E-05	3.92E-05	3.66E-05	1.02E-05	1.40E-04	7.53E-06	3.40E-04	1.52E-05	4.34E-06	1.87E-06	1.53E-03
ADD_{inh}	1.16E-09	1.59E-08	9.53E-08	4.17E-09	7.66E-09	7.64E-09	9.30E-09	1.67E-09	5.93E-09	5.54E-09	1.55E-09	2.12E-09	1.14E-09	5.17E-08	2.30E-09	6.60E-10	2.83E-10	2.14E-07
ADD_{derm}	3.32E-07	5.26E-06	3.14E-05	1.38E-06	2.53E-06	2.52E-06	3.06E-06	5.53E-07	1.96E-06	1.83E-06	5.11E-07	6.90E-06	3.76E-07	1.68E-05	7.59E-09	2.17E-07	9.35E-08	7.57E-05
Total	**7.97E-06**	**1.05E-04**	**6.61E-04**	**2.89E-05**	**5.31E-05**	**5.30E-05**	**6.44E-05**	**1.16E-05**	**4.12E-05**	**3.84E-05**	**1.07E-05**	**1.47E-04**	**7.91E-06**	**3.57E-04**	**1.52E-05**	**4.56E-06**	**1.96E-06**	**1.61E-03**

Table 5.21 Carcinogenic risk assessment for trace elements in soil via ingestion, inhalation, and dermal exposure pathways for children and adult

Pathways	Carcinogenic risk (CR) values for trace elements in soil (mg/kg/day)					Total CR
	Cr	Co	Ni	As	Pb	
Children						
CR_{ing}	6.00E-04	–	8.57E-05	3.09E-05	2.40E-07	7.17E-04
CR_{inh}	9.10E-09	8.16E-10	1.76E-08	5.89E-09	2.24E-11	3.34E-08
CR_{derm}	–	–	–	6.77E-07	–	6.77E-07
CR	**6.00E-04**	**8.16E-10**	**8.57E-05**	**3.16E-05**	**2.40E-07**	**7.18E-04**
Adults						
CR_{ing}	3.15E-04	–	4.60E-05	1.65E-05	1.29E-07	3.78E-04
CR_{inh}	3.91E-08	3.50E-09	7.51E-08	2.52E-09	9.66E-10	1.21E-07
CR_{derm}	–	–	–	2.02E-06	–	2.02E-06
CR	**3.15E-04**	**3.50E-09**	**4.61E-05**	**1.85E-05**	**1.30E-07**	**3.80E-04**

In road dust, the ADD in Table 5.22 and the slope factors in Table 5.15, were used to assess carcinogenic risks of Cr, Ni, As, Pb and Co for both children and adults. This was done using Equations 10 to 13, as described in Chapter 4. The carcinogenic risks of Sc, V, Cu, Zn, Rb, Sr, Y, Zr, Nb, Ba, Th and U were not assessed due to the lack of their carcinogenic slope factors. The carcinogenic risk results are summarised in Table 5.23 as carcinogenic risk and TCR for ingestion, inhalation and dermal pathways.

The TCR in children was 4.15E-04, contributed mostly by ingestion (4.15E-05), followed by dermal (2.59E-07) and inhalation pathways (1.60E-08). The contribution of heavy metals to the TCR was Cr (3.54E-04), Ni (4.98E-05), As (1.21E-05), Pb (2.86E-07) and Co (3.03E-07). In the adult population, the TCR was 2.21E-04. It was contributed mostly by ingestion (2.20E-04), followed by the dermal (7.76E-07) and inhalation pathways (6.85E-08). The carcinogenic risk values of individual heavy metals were Cr (1.87E-04), Ni (2.64E-05), As (7.12E-06), Pb (1.54E-07) and Co (1.30E-09).

The results of carcinogenic risk assessment in road dust revealed the TCR value in children to be 4.15E-04. This risk value was above the acceptable value and has the possibility to cause carcinogenic risk to the children living in this informal settlement.

Central University of Technology, Free State

The carcinogenic risk value was contributed by the ingestion pathway (4.15E-04), with a value above the tolerable value, placing children under the likelihood of developing carcinogenic risks. The total carcinogenic risk values of dermal and inhalation were within the acceptable range, which was an indication of no possibility of carcinogenic risk via these pathways. The total carcinogenic risks through various exposure pathways were ingestion > dermal > inhalation. In this informal settlement, the carcinogenic risk value (3.54E-04) was the major contributor to the TCR. Furthermore, it was above the permissible value, signifying a possibility of children to develop cancer from its exposure. Other trace elements showed no possibility of carcinogenic risks as their values were within the acceptable limit. The health implications of these elements are reported in Section 5.6 of this chapter. The carcinogenic risk values of all the elements were as Cr > Ni > As > Pb > Co. According to various researchers (Candeias et al. 2020; Qadeer et al. 2019; Taiwo et al. 2017, 2020), ingestion of road dust in the children group was the leading contributor to carcinogenic risk, which is comparable to the outcomes of this study. Furthermore, Taiwo et al. (2020) also reported dermal and inhalation to be below the acceptable value, which support the findings of this study. Similar findings confirming Cr to be the main driver to carcinogenic risk was also reported by Dat et al. (2021).

Moreover, the TCR value in adults was 2.21E-04, which was higher than the acceptable value and likely to cause carcinogenic risk in the adult population. The ingestion pathway (2.20E-04), with a value above the acceptable limit, was the major contributor. The carcinogenic risk values of dermal and inhalation pathways were within the acceptable limit. These findings revealed that adults were at risk of developing carcinogenic risks mainly through the ingestion pathway. The total carcinogenic risks through various exposure pathways were ingestion > dermal > inhalation. Furthermore, the carcinogenic risk value of Cr (1.87E-04) was higher than the permissible value, signifying the possibility of adults to develop carcinogenic risk from its exposure. Other heavy metals showed no possibility of carcinogenic risks as their values were within the permissible limits. The contribution of each of the trace elements to carcinogenic risk was as Cr > Ni > As > Pb > Co. Similarly, Dat et al. (2021) and Taiwo et al. (2020) elucidated the ingestion pathway and Cr as the leading contributors to the TCR. Furthermore, they also reported dermal and inhalation to be below the acceptable value, which is in agreement with the findings of this study. The findings of this study also support the results of Taiwo et al. (2017); Shi et al. (2018); and Candeias et al. (2020), which revealed ingestion as the main contributor to carcinogenic risk.

Additionally, the TCR in the children group was higher than the TCR in the adult group, demonstrating that children were at a higher risk than adults (Figure 5.15), which is comparable to the results of other researchers (Dat et al. 2021; Jadoon et al. 2020; Ma and Singhirunnusorn 2012). According to Jadoon et al. (2020), this difference may be due to children's low body mass, behaviours of playing in dust and hand sucking. The ingestion pathway contribution to carcinogenic risk in children was higher than those in the adult population. Furthermore, as presented in Figure 5.16, the value of Cr, which was the main driver to carcinogenic risk in the population of Winnie Mandela informal settlement was high in the children group. These findings clearly demonstrate that the population in this study, particularly children, were confronted with the possibility of carcinogenic risk mainly through ingestion of Cr. From the results of the carcinogenic risk assessment, it was clear that trace elements in road dust had the possibility to contribute to carcinogenic risks for all the population groups as their TCR values were higher than the permissible value, which is in agreement with the finding of Taiwo et al. (2020).

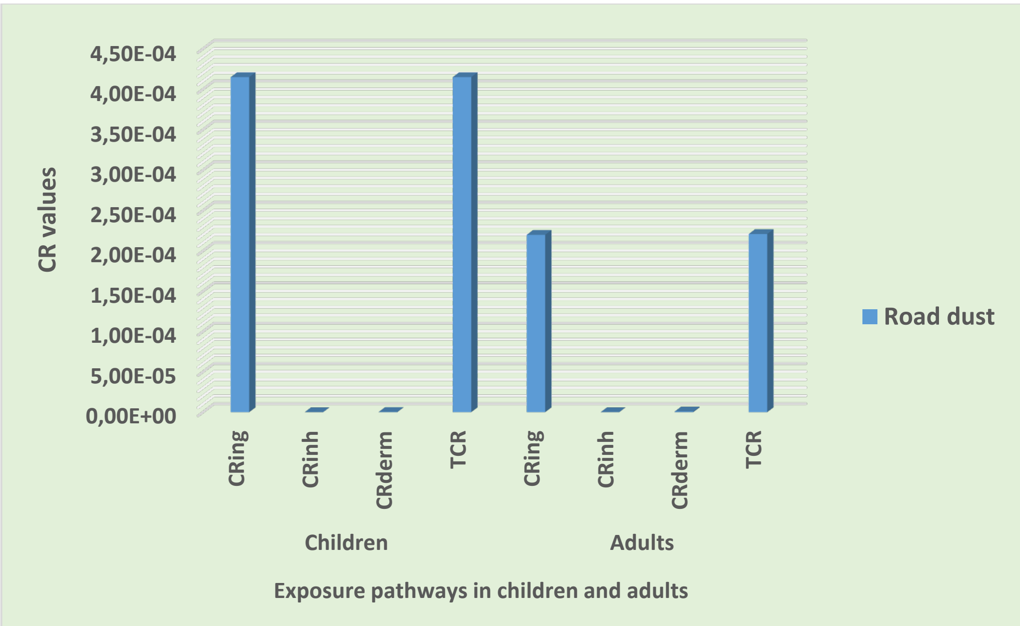

Figure 5.15 Carcinogenic risks of trace elements in road dust for children and adults through various exposure pathways

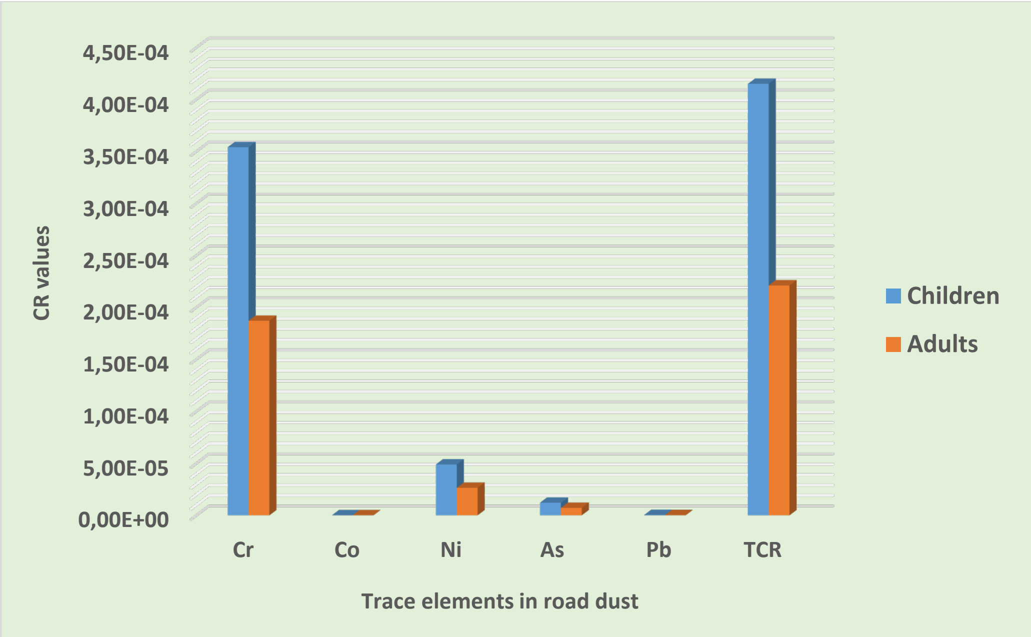

Figure 5.16 Contribution of individual trace elements in road dust to carcinogenic risk for children and adults

Table 5.22 Carcinogenic average daily dose for trace elements in road dust via ingestion, inhalation, and dermal exposure pathways for children and adults

Pathways	Carcinogenic average daily dose (ADD) for trace element in road dust (mg/kg/day)																	Total LADD
	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U	
Children																		
ADDing	7.43E-05	8.80E-04	8.10E-03	2.20E-04	6.30E-04	7.80E-04	2.90E-03	9.20E-05	8.43E-04	1.53E-03	1.84E-04	2.43E-03	1.11E-04	8.00E-03	3.90E-04	5.85E-05	3.70E-05	2.73E-02
ADDinh	1.40E-09	1.70E-08	1.54E-07	4.21E-09	1.20E-08	1.50E-08	5.61E-08	1.74E-09	1.60E-08	2.91E-08	3.50E-09	4.60E-08	2.09E-09	1.51E-07	7.46E-09	1.10E-09	7.02E-10	5.18E-07
ADDderm	6.67E-09	7.94E-06	7.33E-05	2.00E-06	5.64E-06	7.02E-06	2.67E-05	8.30E-07	7.59E-06	1.40E-05	1.66E-06	2.20E-06	9.90E-07	7.20E-05	3.54E-06	5.27E-07	3.34E-07	2.26E-04
Total	**7.43E-05**	**8.88E-04**	**8.17E-03**	**2.22E-04**	**6.36E-04**	**7.87E-04**	**2.93E-03**	**9.28E-05**	**8.51E-04**	**1.54E-03**	**1.86E-04**	**2.43E-03**	**1.12E-04**	**8.07E-03**	**3.94E-04**	**5.90E-05**	**3.73E-05**	**2.75E-02**
Adults																		
ADDing	9.94E-06	1.20E-04	1.10E-03	2.98E-05	8.40E-05	1.00E-04	4.00E-04	1.23E-05	1.13E-04	2.06E-04	2.47E-05	3.26E-04	1.47E-05	1.07E-03	5.28E-05	7.86E-06	4.97E-06	3.68E-03
ADDinh	1.50E-09	1.80E-08	1.66E-07	4.52E-09	1.30E-08	1.60E-08	6.02E-08	1.90E-09	1.71E-08	3.12E-08	3.74E-09	4.94E-08	2.23E-09	1.62E-07	8.00E-09	1.20E-09	7.54E-10	5.57E-07
ADDderm	4.97E-07	5.92E-06	5.50E-05	1.49E-06	4.20E-06	5.23E-06	1.99E-05	6.17E-07	5.66E-06	1.03E-05	1.23E-06	1.63E-05	7.40E-07	5.40E-05	2.64E-06	3.93E-07	2.49E-07	1.84E-04
Total	**1.04E-05**	**1.26E-04**	**1.16E-03**	**3.13E-05**	**8.82E-05**	**1.05E-04**	**4.20E-04**	**1.29E-05**	**1.19E-04**	**2.16E-04**	**2.59E-05**	**3.42E-04**	**1.54E-05**	**1.12E-03**	**5.54E-05**	**8.25E-06**	**5.22E-06**	**3.86E-03**

Table 5.23 Carcinogenic risk assessment for trace elements in road dust via ingestion, inhalation, and dermal exposure pathways for children and adults

Pathways	Carcinogenic risk (CR) values for trace elements in road dust (mg/kg/day)					Total CR
	Cr	Co	Ni	As	Pb	
Children						
CRing	3.54E-04	–	4.89E-05	1.18E-05	2.86E-07	4.15E-04
CRinh	5.41E-09	3.03E-10	9.99E-09	2.26E-10	2.68E-11	1.60E-08
CRderm	–	–	–	2.59E-07	–	2.59E-07
CR	**3.54E-04**	**3.03E-10**	**4.89E-05**	**1.21E-05**	**2.86E-07**	**4.15E-04**
Adults						
CRing	1.87E-04	–	2.64E-05	6.34E-06	1.54E-07	2.20E-04
CRinh	2.33E-08	1.30E-09	4.28E-08	9.69E-10	1.15E-10	6.85E-08
CRderm	–	–	–	7.76E-07	–	7.76E-07
CR	**1.87E-04**	**1.30E-09**	**2.64E-05**	**7.12E-06**	**1.54E-07**	**2.21E-04**

5.6 Health implications associated with trace element exposure in soil and road dust

In the soil and road dust of Winnie Mandela informal settlement, 17 trace elements (Cr, Co, Cu, Zr, As, V, Pb, Ni, Nb, Zn, Sc, Ba, U, Y, Th, Rb, Sr) were examined. Among them, As, Ba, Co, Cr, Cu, Nb, Ni, Pb, Zn, V and Zr were above their average shale values. In this study, trace elements above their average shale values were regarded as toxic and of public health concern. Their exposure may lead to serious health implications to the local inhabitants which are described in the following subsections.

5.6.1 Arsenic

According to Nadal (2005), As is regarded as a cancer-causing element to humans at low concentrations. The long-term exposure of As by residents of Winnie Mandela informal settlement may result in health implications such as skin, lung, bladder, prostrate and blood cancer, as well as miscarriages (Heck et al. 2014; Nizam et al. 2013; Okereafor et al. 2020). Noncarcinogenic effects as a result of exposure to As may include nervous and cardiovascular effects (Nadal 2005).

5.6.2 Barium

Ba is an essential element. However, its long-term exposure may cause medical conditions such as alteration of myocardial contractility, high blood pressure, renal failure, lung sclerosis, hearing loss and nervous system disorders to the population living in this informal settlement (Kravchenko et al. 2014).

5.6.3 Cobalt

Inhabitants of Winnie Mandela informal settlement may experience reduced pulmonary functions, an increased rate of coughing, respiratory inflammation and lung fibrosis as a result of Co exposure. Furthermore, health implications such as brachial plexus neuropathy, damage of hearing and visual impairment may also occur to the population living in this informal settlement due to long-term exposure to Co (Leyssens 2017; Sheikh 2016).

5.6.4 Chromium

Cr is found in the form of either trivalent Cr (III) or hexavalent Cr (VI). The trivalent chromium is regarded as an essential nutrient to humans, whereas the hexavalent chromium is highly toxic (Nadal 2005). Exposure to high levels of Cr may cause residents of Winnie Mandela informal settlement to experience several health implications such as liver disorder, asthma, chronic bronchitis, irritation, pharyngitis, rhinitis, renal failure, lungs, nasal and sinus cancers (Abdel-Gadir 2016; Brutti 2013; Ray 2016).

5.6.5 Copper

Cu is considered to be an element that is vital for life; however, its exposure may lead to noncarcinogenic effects. Irritation of the nose, mouth and eyes, headaches, dizziness, nausea, vomiting, and stomach cramps may be some of the health implications that the population living in this informal settlement may suffer as a result of exposure to Cu. It may also cause damage of the liver, brain and kidney, as well as renal disease or even death to the local residents (Okereafor et al. 2020).

5.6.6 Niobium

The information on toxicological effects of Nb is dearth. However, according to Dierks (1991), Nb as a rare earth element is moderately to highly toxic and the community of Winnie Mandela informal settlement may suffer health implications such as writhing, ataxia, difficulties in breathing, skin irritation, eye irritation, and lung granulomas due to exposure to high concentrations of Nb (Reference?).

5.6.7 Nickel

According to Singo (2013), Ni is known to be a carcinogenic element. The inhabitants of Winnie Mandela informal settlement may develop lung cancer, nasal cancer, sinus cancer, chronic bronchitis (Carver and Gallicchio, 2018), nausea, vomiting, abdominal pain, diarrhoea, headaches, coughing, shortness of breath and dizziness (Okereafor et al. 2020) as a result of exposure to high concentrations of Ni in soil and road dust.

5.6.8 Lead

Pb is regarded as toxic at low levels (Okereafor et al. 2020) and carcinogenic to humans (Singo 2013). Pb exposure may result in miscarriages, hormonal changes, reduced potency in humans, menstrual abnormalities, puberty interruptions in girls, loss of memory, mood swings, muscle disorders, as well as cardiovascular, skeletal, kidney and renal problems (Aremu 2008).

5.6.9 Zinc

Zn may cause noncarcinogenic effects, although it is vital for life. Exposure to Zn may cause medical conditions such as respiratory disorders, epigastric pains, risks of prostate cancer, exhaustion, acute renal tubular necrosis and interstitial nephritis (Okereafor et al. 2020).

5.6.10 Vanadium

Nausea, vomiting and mild neurological effects may occur as a result of V exposure, specifically via ingestion (Agency for toxic substances and disease registry 2017). V exposure may also affect reproductive and developmental processes of local residents (Nadal 2005).

5.6.11 Zirconium

As a result of exposure to Zr, Winnie Mandela informal settlement population may experience pulmonary health effects such as pulmonary oedema and pulmonary granulomas. Furthermore, health implications such as mucosal irritation, hoarseness and dyspnoea may occur in the settlement dwellers as a result of exposure to Zr (Liippo et al. 1993).

5.7 Conclusions

The activities in an urban informal settlement contributed more to the accumulation of trace elements in soil and road dust. The results of pollution indices showed soil and road dust of Winnie Mandela informal settlement to be polluted by trace elements, mainly by Cr. The health risk assessment results also revealed trace elements in soil and road dust to have the potential to contribute to noncarcinogenic and carcinogenic risks to the local residents. Children were at high risk of both noncarcinogenic and carcinogenic risk as compared to the adult group. Some of the possible health implications as a result of heavy metal exposure are cancer, miscarriages, lung fibrosis, hearing and visual impairment, asthma, renal failure, high blood pressure, headaches and dizziness, vomiting, damage of liver, and cardiovascular disorders. Furthermore, studies investigating trace element pollution in soil and road dust from informal settlements are needed for protection of the environment and safety of residents.

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CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The overall aim of this study was to give an overview on the concentration of heavy metal in soil and road dust from Winnie Mandela informal settlement in the Gauteng province, South Africa, and evaluate its possible health risks. The lack of information on heavy metal concentration and a concern for the public health motivated the undertaking of this study. The study concludes that informal settlements are unsustainable and impact the environment negatively, thus making poor an informal settlement unsafe for human habitation. Seventeen (17) trace elements, namely Cr, Co, Cu, Zr, As, V, Pb, Ni, Nb, Zn, Sc, Ba, U, Y, Th, Rb, Sr were found accumulating in soil and road dust, and among them As, Ba, Co, Cr, Cu, Nb, Ni, Pb, Zn, V and Zr were above their average shale values. Activities such as dense traffic, poor waste management, use of charcoal for household heating and cooking, unregulated waste incineration, unplanned construction and sewage waste water that runs on the streets in this urban informal settlement have a considerable influence on the accumulation of these trace elements in soil and road dust during the winter season. The outcomes of all the pollution indices revealed soil and road dust to be highly contaminated by Cr. The high concentration of Cr in soil and road dust may put the population of Winnie Mandela informal settlement at health risks. Exposure to high concentrations of Cr by local inhabitants may cause serious health implications such as liver disorder, asthma, chronic bronchitis, irritation, pharyngitis, rhinitis, renal failure, and lung, nasal and sinus cancers. Furthermore, other trace elements may also lead to miscarriages, hearing and visual impairment, high blood pressure, headaches and dizziness, vomiting, and cardiovascular disorders. Additionally, the level of trace elements in soil and road dust of Winnie Mandela informal settlement showed the potential to contribute to noncarcinogenic and carcinogenic risks to the local residents. Children were at high risk of both noncarcinogenic and carcinogenic risk as compared to the adult group. Furthermore, daily population rise, unplanned construction, unregulated waste burning and ongoing poor waste management may further exacerbate the

Central University of Technology, Free State

accumulation of heavy metals and possible health implications in the future, thus making the settlement unsustainable and unsafe for the local inhabitants.

6.2 Recommendations

The current findings will serve as useful information concerning the trace element pollution in soil and road dust from urban informal settlements. Winnie Mandela informal settlement is contaminated with trace elements, consequently the following recommendations are made for population safety and future studies:

- Awareness of the present contamination of soils and road dust is needed for the protection and safety of the community.
- Proper waste management within the settlement is also recommended.
- Residents should engage in community servicing such as collecting and managing their waste through recycling/reuse and also avoid burning of waste.
- The community should also be educated on the importance of the environment, pollution, waste management and health.
- Remediation, cleaning and regular monitoring of heavy metals is desirable for the safety of the inhabitants and sustainability of the settlement.
- The study can also be expanded to cover the assessment of levels of heavy metals in surface water, atmospheric suspended particles and on vegetation along the roads.
- The overall health risk assessment of trace elements in this study did not take into account the size of road dust particles, thus future work should cover the variation in particle size distribution and morphology during different seasons of the year.
- Health risk assessment of indoor dust should also be considered for future studies.
- The outcomes of the study revealed the possibility of Cr to cause noncarcinogenic and carcinogenic risk; however, its carcinogenic causing class was not covered in this study, which is recommended for future studies.

Appendix A

SUPPLEMENTARY INFORMATION TO CHAPTER 5

Summary of mineralogical analysis of soil and road dust

XRD results for soil samples (Wt. %)											
Sample ID	Quartz	Plagioclase	K-feldspar/ rutile	Calcite	Dolomite	Mica	Serpentine	Clino-chlore	Pyrite	Cordierite	Hematite
SL01	39	10	6	–	–	15	12	-	–	11	7
SL02	50	8	9	–	–	13	12	–	–	–	8
SL03	44	8	8	2	4	13	13	–	–	–	8
SL04	52	8	8	–	–	12	13	–	–	–	7
SL05	50	8	9	–	3	12	11	–	–	–	7
Min	39	8	6	2	3	12	11	–	–	11	7
Max	52	10	9	2	4	15	13	–	–	11	8
Mean	47	8.4	8	2	3.5	13	12.2	–	–	11	7.4
SD	5.4	0.9	1.2	0	0.7	1.2	0.8	–	–	–	0.5
XRD results for road dust samples (Wt. %)											
Sample ID	Quartz	Plagioclase	K-feldspar/ rutile	Calcite	Dolomite	Mica	Serpentine	Clino-chlore	Pyrite	Cordierite	Hematite
RD01	64	7	8	2	4	9	6	–	–	–	–
RD02	48	9	10	3	8	13	9	–	–	–	–
RD03	64	6	5	–	4	9	–	8	4	–	–
RD04	65	6	8	2	3	9	7	–	–	–	–
RD05	57	6	7	2	4	9	8	–	–	7	–
Min	48	6	5	2	3	9	6	8	4	7	–
Max	65	9	10	3	8	13	9	8	4	7	–
Mean	59.6	6.8	7.6	2.25	4.6	9.8	7.5	8	4	7	–
SD	7.2	1.3	1.8	0.5	1.9	1.8	1.3	–	–	–	–

Summary of major elements analysis in soil and road dust

XRF results for soil sample (Wt. %)												
Sample Id	**SiO_2**	**TiO_2**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**MnO**	**CaO**	**Na_2O**	**K_2O**	**P_2O5**	**LOI**	**Total**
SL01	65.92	0.77	11.65	7.78	0.35	0.62	0.75	0.36	1.61	0.19	8.22	98.22
SL02	67.32	0.77	10.39	8.14	0.29	2.27	0.85	0.13	0.74	0.11	7.03	98.03
SL03	67.91	0.97	11.59	8.10	0.41	0.57	1.01	0.12	0.66	0.17	8.42	99.91
SL04	68.26	0.76	11.01	8.11	0.11	0.55	0.38	0.12	0.58	0.13	7.12	97.12
SL05	70.59	0.73	9.29	6.95	0.26	0.80	0.72	0.22	0.95	0.19	6.70	97.42
Min	65.92	0.73	9.29	6.95	0.11	0.55	0.38	0.12	0.58	0.11	6.70	97.12
Max	70.59	0.97	11.65	8.14	0.41	2.27	1.01	0.36	1.61	0.19	8.42	99.91
Mean	68.00	0.80	10.79	7.82	0.28	0.96	0.74	0.19	0.91	0.16	7.50	98.14
SD	1.70	0.10	0.98	0.51	0.11	0.74	0.23	0.10	0.42	0.04	0.77	1.09
XRF results for road dust samples (Wt. %)												
Sample Id	**SiO_2**	**TiO_2**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**MnO**	**CaO**	**Na_2O**	**K_2O**	**P_2O5**	**LOI**	**Total**
RD01	69.17	0.36	7.22	3.41	1.18	0.42	4.23	0.98	1.43	0.12	11.30	99.83
RD02	65.37	0.35	8.43	3.52	1.15	0.24	3.62	1.89	2.44	0.37	10.52	97.89
RD03	75.07	0.46	6.21	3.68	0.72	0.66	1.97	0.71	1.27	0.11	7.47	98.31
RD04	79.92	0.35	5.90	4.11	0.32	1.03	1.09	0.76	1.45	0.08	4.98	99.98
RD05	74.25	0.48	6.72	4.67	1.33	0.51	2.66	0.62	1.22	0.12	6.61	99.18
Min	65.37	0.35	5.90	3.41	0.32	0.24	1.09	0.62	1.22	0.08	4.98	97.89
Max	79.92	0.48	8.43	4.67	1.33	1.03	4.23	1.89	2.44	0.37	11.30	99.98
Mean	72.76	0.40	6.90	3.88	0.94	0.57	2.71	0.99	1.56	0.16	8.18	99.04
SD	5.62	0.06	0.99	0.52	0.41	0.30	1.26	0.52	0.50	0.12	2.67	0.92

Summary of trace elements analysis in soil and road dust

Heavy metals concentration in soil samples mg/kg)																	
ID	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U
SL01	13	184	652	54	85	86	107	14	97	86	22	227	15	513	14	10	3
SL02	13	191	2361	38	142	58	66	10	64	76	21	224	12	544	15	9	2.9
SL03	16	189	452	48	72	134	106	18	52	45	16	232	12	450	9	9	3
SL04	12	181	1203	53	72	64	91	42	55	41	11	265	13	655	70	2.9	3
SL05	11	149	682	41	59	87	151	10	65	63	17	240	12	704	21	6	4
Min	11	149	452	38	59	58	66	10	52	41	11	224	12	450	9	2.9	2.9
Max	16	191	2361	54	142	134	151	42	97	86	22	265	15	704	70	10	4
Mean	13	178.8	1070	46.8	86	85.8	104.2	18.8	66.6	62.2	17.4	237.6	12.8	573.2	25.8	7.38	3.18
SD	1.9	17.1	773.2	7.1	32.6	29.9	31.0	13.4	17.9	19.4	4.4	16.5	1.3	104.2	25.1	2.9	0.5
Heavy metals concentration in road dust samples (mg/kg)																	
ID	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U
RD01	7	57	493	16	37	125	700	9	61	156	15	164	9	563	32	6	2.9
RD02	8	55	283	15	32	42	131	10	82	153	14	167	8	636	17	6	2.9
RD03	4	76	694	17	53	45	147	4	59	99	14	221	9	546	30	5	2.9
RD04	5	75	1088	20	80	43	67	4	72	81	14	172	8	729	41	2.9	2.9
RD05	5	82	629	19	43	50	114	9	56	112	15	227	9	654	34	3	2.9
Min	4	55	283	15	32	42	67	4	56	81	14	164	8	546	17	2.9	2.9
Max	8	82	1088	20	80	125	700	10	82	156	15	227	9	729	41	6	2.9
Mean	5.8	69	637.4	17.4	49	61	231.8	7.2	66	120.2	14.4	190.2	8.6	625.6	30.8	4.58	2.9
SD	1.6	12.2	297.0	2.1	19.0	35.9	263.4	2.9	10.8	33.2	0.5	31.1	0.5	73.9	8.8	1.5	–

Appendix B
TURNITIN REPORT

Appendix C

CONFIRMATION LETTER FROM LANGUAGE EDITOR

Letter of Confirmation

DORATHEA (DORA) DU PLESSIS
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24 May 2022

CONFIRMATION OF EDITING AND PROOFREADING

I hereby confirm that I have done the technical layout and language editing of the following master's dissertation:

Student:	Innocent Mugudamani
Title:	Geochemical characterisation of soil and road dust from an informal settlement and their possible health implications: A study of Winnie Mandela informal settlement, Gauteng, South Africa
Degree:	Master of Health Sciences: Environmental Health
University:	Central University of Technology, Free State

My work for the student included the technical layout of the document on a specific Microsoft Word template that I created for the student. I checked all acronyms and abbreviations for consistent use in the text. Language editing included grammar, punctuation, spelling, and sentence structure. I tried to keep as much as possible of the student's own writing style, while making sure that the student's intended meaning was not altered in the process. I did not cross-check the list of references. All amendments were tracked with the Microsoft Word track changes feature. The student thus had the option to accept or reject the changes.

I have more than 40 years of experience in typing, editing, and proofreading for postgraduate students from universities all over South Africa and now also abroad. I gained my experience during the years I was typing student dissertations and theses and while working at different departments at the UFS from 1978 to 1981 and again from 1998 to 2014. I also assisted in compiling a document on technical layout and referencing methods for the Centre for Environmental Management (CEM) and have presented guest lectures on referencing methods to postgraduate students at CEM and the Department of Urban and Regional Planning at the UFS.

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additions or deletions to the document, or any language issues that may have emerged as a result of subsequent amendments to the text.

Yours sincerely

Dorathea (Dora) du Plessis
Technical & Language Editor

toxics

Article

Influence of Urban Informal Settlements on Trace Element Accumulation in Road Dust and Their Possible Health Implications in Ekurhuleni Metropolitan Municipality, South Africa

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Abstract: The study was aimed at assessing the influence of urban informal settlement on trace element accumulation in road dust from the Ekurhuleni Metropolitan Municipality, South Africa, and their possible health implications. The concentration of major and trace elements was determined using the wavelength dispersive XRF method. The major elements in descending order were SiO_2 (72.76%), Al_2O_3 (6.90%), Fe_2O_3 (3.88%), CaO (2.71%), K_2O (1.56%), Na_2O (0.99%), MgO (0.94%), MnO (0.57%), TiO_2 (0.40%), and P_2O_5 (0.16%), with SiO_2 and P_2O_5 at above-average shale values. The average mean concentrations of 17 trace elements in decreasing order were Cr (637.4), Ba (625.6), Zn (231.8), Zr (190.2), Sr (120.2), V (69), Rb (66), Cu (61), Ni (49), Pb (30.8), Co (17.4), Y (14.4), Nb (8.6), As (7.2), Sc (5.8), Th (4.58), and U (2.9) mg/kg. Trace elements such as Cr, Cu, Zn, Zr, Ba, and Pb surpassed their average shale values, and only Cr surpassed the South African soil screening values. The assessment of pollution through the geo-accumulation index (Igeo) revealed that road dust was moderately to heavily contaminated by Cr, whereas all other trace elements were categorized as being uncontaminated to moderately contaminated. The contamination factor (CF) exhibited road dust to be very highly contaminated by Cr, moderately contaminated by Zn, Pb, Cu, Zr, and Ba, and lowly contaminated by Co, U, Nb, Ni, As, Y, V, Rb, Sc, Sr, and Th. The pollution load index (PLI) also affirmed that the road dust in this study was very highly polluted by trace elements. Moreover, the results of the enrichment factor (EF) categorized Cr as having a significant degree of enrichment. Zn was elucidated as being minimally enriched, whereas all other trace elements were of natural origin. The results of the non-carcinogenic risk assessment revealed a possibility of non-carcinogenic risks to both children and adults. For the carcinogenic risk, the total CR values in children and adults were above the acceptable limit, signifying a likelihood of carcinogenic risk to the local inhabitants. From the findings of this study, it can be concluded that the levels of trace elements in the road dust of this informal settlement had the possibility to contribute to both non-carcinogenic and carcinogenic risks, and that children were at a higher risk than the adult population.

Keywords: informal settlement; trace elements; road dust; health implications; carcinogenic; non-carcinogenic

1. Introduction

The urban landscape of most developing nations has experienced a proliferation of informal settlements over many years [1], and the majority of Sub-Saharan African urban inhabitants (~55%) now reside in informal settlements [2]. Informal settlements are regarded as being neglected portions of cities where housing and living conditions are terribly poor. They vary from overcrowded, contaminated dwellings to inadvertent squatter locations with no legitimate rights, distributed at the edge of cities [3]. They are seriously characterized by man-made activities such as household heating, the combustion of coal and oil, industrial processes, unplanned construction, demolition activities, road weathering, poor waste management, the burning of waste, and dense traffic [4,5]. Such anthropogenic activities lead to the accumulation of trace elements on buildings, plants, in air, soil, water, and on road dust. Trace elements are not decomposable, and consequently, they persist for long periods of time in the environment [6]. Road dust refers to the re-suspended particulate matter found on roads, mostly in troughs. It sometimes comprises of soil and sand particles that are assorted with litter, and rubble that becomes airborne due to traffic movements [7]. As a results of traffic movements, road dust is frequently raised up, settled, and raised again, to a certain elevation, which exposes residents to any trace elements that are available in such dust [8]. Some of the trace elements connected to road dust are As (arsenic), Ba (barium), Co (cobalt), Cr (chromium), Cu (copper), Ni (nickel), Pb (lead), Zn (zinc), Zr (zirconium), [9] Nb (niobium), Rb (rubidium), Sc (scandium), Sr (strontium), Th (thorium), V (vanadium), and Y (yttrium). Exposure to road dust containing these trace elements, either through inhalation, ingestion, or dermal contact absorption [10] may ultimately lead to serious health implications on the local residents. These include medical conditions such as cancer, miscarriages, hearing and visual impairment, asthma, renal failure, high blood pressure, headaches and dizziness, problems of reproductive systems, cardiovascular disorder, writhing, ataxia, skin and eye irritation, and lung granulomas [11,12]. In South Africa, informal settlements are home-based areas to masses of households, and Ekurhuleni is a metropolitan municipality with roughly 26 percent of its inhabitants residing in informal settlements [13]. These areas are characterized by a lack of proper sanitation, dense traffic, human activities such as a high population, unplanned construction, poor waste management, unregulated waste incineration, charcoal burning, and sewage runoff onto the streets. All of these man-made activities may influence the proliferation of trace elements in road dust, and thus endanger the health of the local inhabitants. Therefore, studying the influence of urban informal settlements on trace element accumulation in road dust is not only an essential aspect of assessing the quality of urban informal settlement settings, but also of protecting the health of the local residents. Despite the available knowledge on the possible effects of trace elements in road dust on public health in South Africa and in other parts of the world, overpopulated informal settlements in South Africa are lacking scientific data on the concentration of trace elements and their associated health risks. Therefore, this study aim to fill in this lacuna by determining the concentration of trace elements, assessing their pollution levels and possible sources, evaluating the health risks, and determining possible health implications that are associated with trace element exposure in road dust. The findings of this study will provide scientific knowledge on the levels of trace elements in road dust, and create awareness about the potential health risks associated with trace element exposure for populations living in poor urban informal settlements.

2. Materials and Methods

2.1. Study Area

The study area is situated within Ekurhuleni Metropolitan Municipality in Gauteng Province, South Africa (Figure 1). The area is positioned 15 km north of Kempton Park City Centre, and approximately 39.4 km south of Pretoria. It consists of 41,581 households with a population of 91,646, and is mostly dominated by approximately 99% Black Africans over a surface area of 5.43 km^2. The area experiences some rainfall, mainly during summer. It is frequently characterized by an average mean annual rainfall of 60 mm. January is considered to be the wettest month, with an average of approximately 125 mm. The month of July is the driest month, with an average of approximately 4 mm. Furthermore, the average mean annual temperature is 16 °C, with January being the warmest, at an average of 20.1 °C, whereas June is considered to be the coldest month, at an average of 10.1 °C.

The study is characterized by human activities such as a high population, unplanned construction, poor waste management, unregulated waste incineration, charcoal combustion, firewood, and sewage waste runoff onto the streets. The settlement is decorated by barbecuing markets along the street, which bisect the settlement. Furthermore, the community transportation system functions with taxicabs, which are the most commonly used method of conveyance by inhabitants. Traffic congestion is noteworthy during the early morning and late afternoon peak hours on the main road that bisect the settlement. There is also an industrial area that is situated approximate 2 to 3 km away from the settlement, which acts as a source of employment for the residents. The area is underlain by Archean Cratonic rocks allocated to the Johannesburg Dome, also recognized as the halfway house or the Johannesburg-Pretoria Dome. The Johannesburg Dome is a dome-like window of ancient granitoid (approximately 750 km^2) positioned in the middle part of the Kaapval Craton. It consist of black reef formation which form the base of the Transvaal Supergroup, which is an outcropping to the north-eastern, northern, and north-western margin of the inlier, and un-conformably overlies the granitoids and greenstones. It also comprises of trondhjemitic and tonalitic granitic rocks intruded into mafic-ultramafic greenstones. Furthermore, it encompasses some hornblende-amphibolites dykes and dolomites of the Chuniespoort group, as shown in Figure 2 [14].

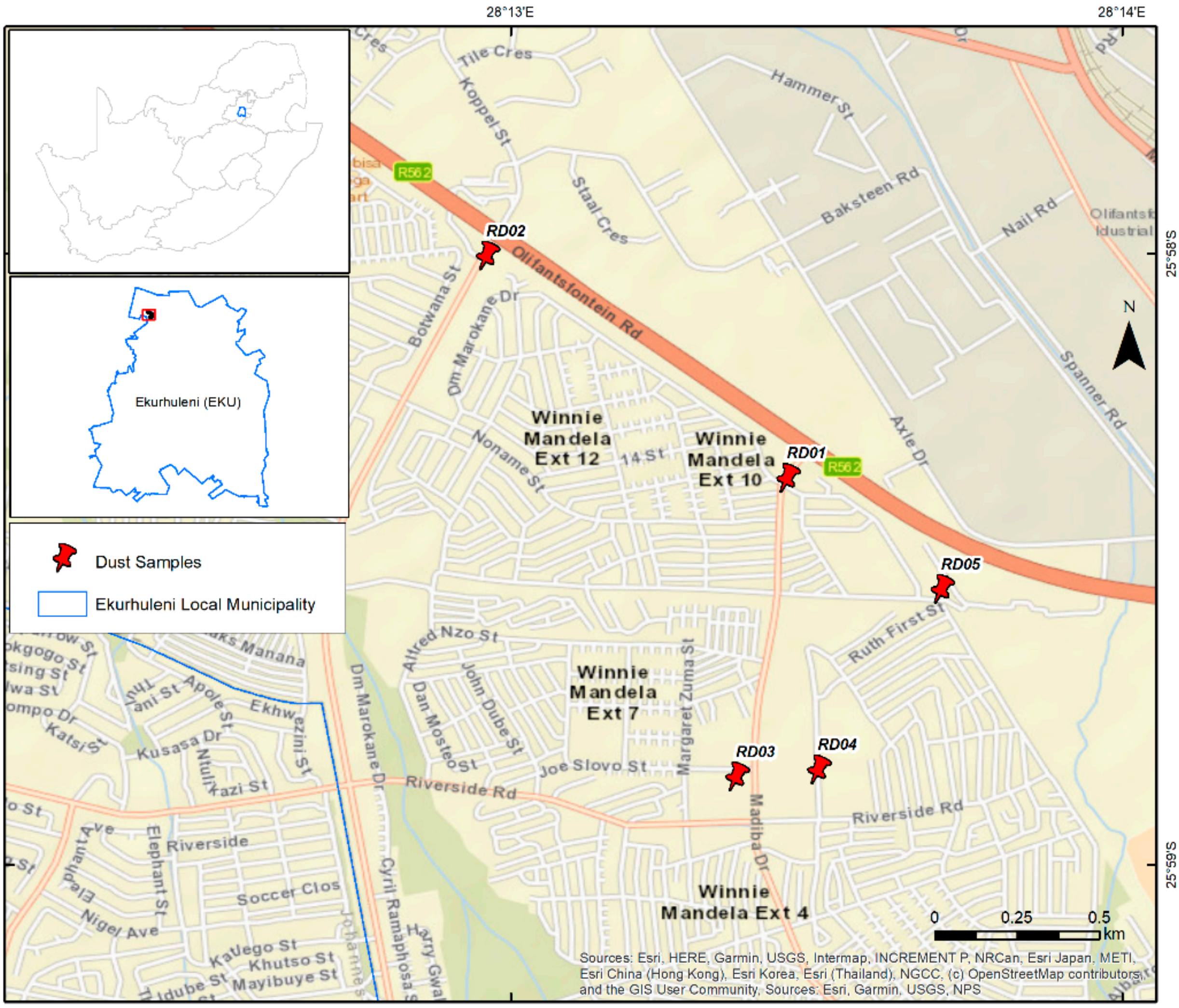

Figure 1. Study area and the location of the sampling site.

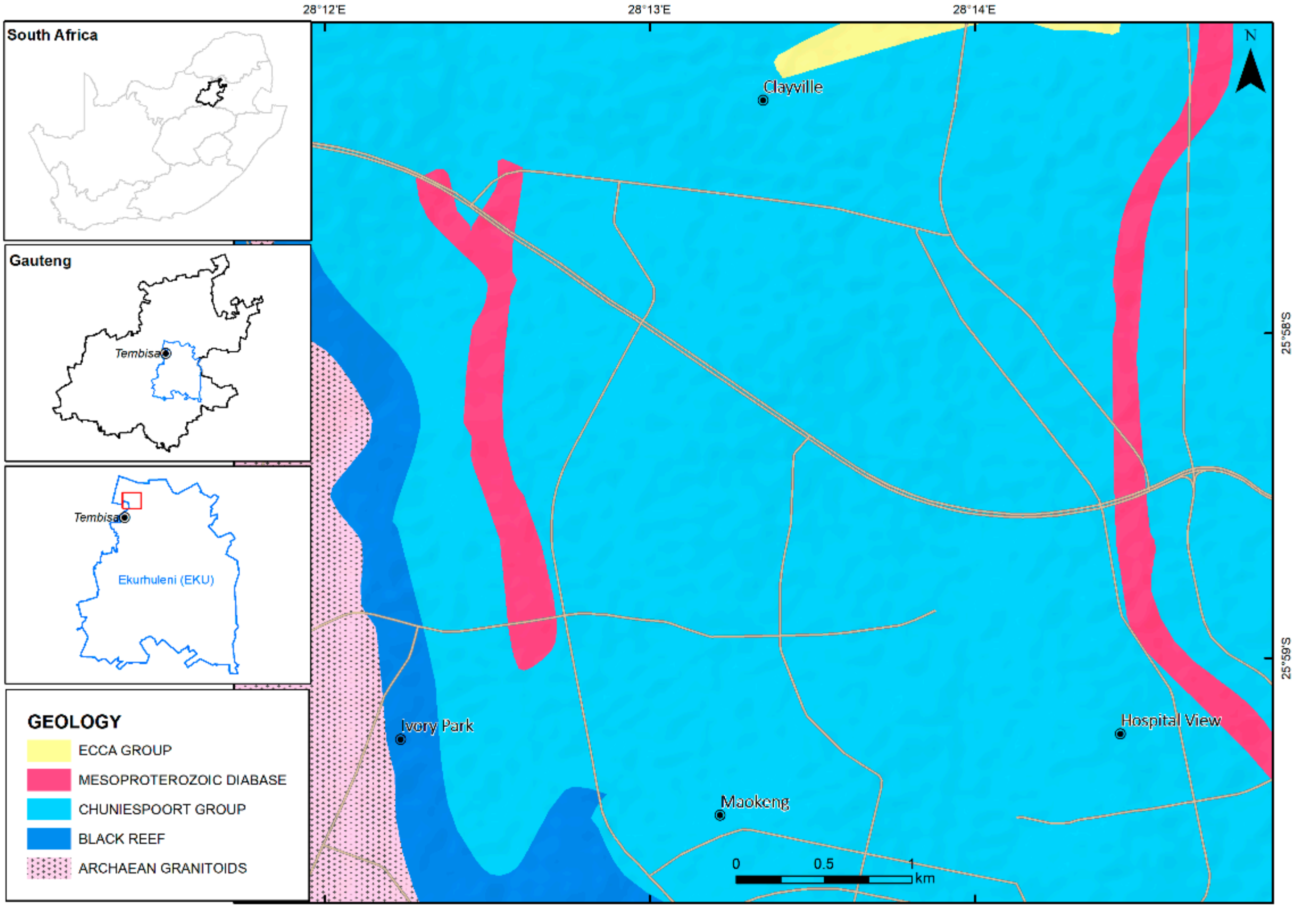

Figure 2. Geological map of the study area.

2.2. Sample Collection and Chemical Analysis

The study area is characterized by different functional areas that include commercial, residential, roadway, taxi rank, and leisure parks/playing grounds. Five (5) road dust samples were collected from these different functional areas, using a random sampling method. The samples were exactly collected at one of the major roads that bisect the settlement, near the park, at the taxi rank, next to the primary school, and at the shopping mall, in order to cover all of the functional areas around the settlement. The points were recorded using GPS, as detailed in Table 1. A sampling campaign was conducted in June 2021, which is a dry month. The road dust particles within a 5 m range of the chosen sampling point were collected by sweeping with a brush and dustpan. A randomly selected sample was collected on a paved surface, and the sampling points are presented in Figure 1. Unrelated material such as litter and debris were taken out from the samples in the course of sampling. To avoid cross-contamination, equipment was cleaned after every location. The samples were then transferred into the plastic sample bags, labelled, and conveyed to the laboratory.

A total of 10 g of sample was ground to a particle size of less than 200 mesh. The 10 g sample was then heated to 110 °C to dehydrate and devolatilize the sample, and then to 1050 °C, which breaks down minerals such as carbonates. This was conducted to determine the total loss on ignition, or the total gain on ignition. Then, a flux of 0.2445 g of La_2O_3, 0.705 g of $Li_2B_4O_7$, 0.5505 g of Li_2CO_3, and 0.02 g of $NaNO_3$ was added to 0.28 g of sample. The mixture was then heated to 1000 °C for approximately 5 min until a consistent fluid was formed within a Pt crucible. The fluid was then poured into a mold and pressed to form the disc. The application used to measure the majors was "IGS majors". It was created using the following standards: DR-N, JB-2, JF-2, JG-2, JGB-1, K8000, MA-N, MICA-

FE, MRG-1, NIM-S, SARM4, SARM5, SARM6, SARM43, SARM44, SARM47, SARM48, SARM50, SARM52, SY-2, and UB-N for quality control.

Table 1. Location and characteristics of sampling points.

Sample ID.	Description	GPS Coordinates	
		Latitude	Longitude
RD01	At one of the major roads (Madiba drive)	25°58′22.1″ S	28°13′27.1″E
RD02	At the southward drive, near the park	25°58′00.3″ S	28°12′57.6″ E
RD03	At the community taxi rank	25°58′51.4″ S	28°13′22.1″ E
RD04	Next to primary school gate	25°58′50.7″ S	28°13′30.1″ E
RD05	Within the community shopping centre or mall	25°58′33.0″ S	28°13′42.2″ E

To analyze the trace elements, 8 g of sample was added to 3 g of Hoechst wax ($C_6H_8O_3N_2$). It was then mixed for 20 min in a Turbula mixer to ensure that the sample was mixed until it was homogeneous. The mixture was then pressed to pressures of greater than 395 N/m. The calibrated application used for the trace elements analysis was 'UIC traces', and for the analysis of Na, it was 'Sodium only'. The standards used to calibrate the 'UIC traces' included: ASK-2, ASK-3, BE-N, BHVO-1, BR, GA, GH, JA-1, JB-1, JB-2, JDO-1, JG-1, JG-2, JLS-1, JP-1, JR-1, JR-2, K8000, MA-N, MICA-FE, MICA-MG, MRG-1, NIM-D, NIM-G, NIM-L, NIM-N, NIM-P, NIM-S, RGM-1, SY-2, TRABS-001, TRABS-002, TRABS-003, TRABS-004, TRACE-000, TRACE-001, TRACE-002, TRACE-003, TRACE-004, TRACE-005, TRACE-006, TRACE-007, TRACE-008, TRACE-009, TRACE-010, TRACE-011, TRACE-012, TRACE-013, TRACE-014, TRACE-015, TRACE-016, TRMAC-001, TRMAC-002, TRMAC-003, TRMAC-004, TRMAC-005, TRMAC-006, UB-N, and VS-N for the quality control. CaO, TiO_2, and Fe_2O_3 were measured to correct for line overlaps. The standards used to calibrate 'Sodium only' included: AN-G, BR, FK-N, G2, GA, GH, GS-N, GSP-1, JG-1, NIM-G, NIM-N, NIM-P, NIM-S, SARM39, and SY-2. Blank samples and duplicates were also used to determine precision and bias. The level of inconsistency was determined to be <10%. The WD-XRF machine used in this study was a Rigaku-Primus IV, with an Rh tube. The software used for the machine was ZXS, and the results are quantitative results.

2.3. Pollution Assessment of Trace Elements in Road Dust

2.3.1. Geo-Accumulation Index (Igeo)

This involves matching the level of the determined trace element to the average shale value or background levels [15,16]. This was computed using Equation (1):

$$\text{Igeo} = \log_2 (\text{Cn}/1.5\ \text{Bn}) \quad (1)$$

where Cn signifies the measured concentration in this study, and Bn represents the geochemical background value or an average shale value of an element of interest. A constant of 1.5 is presented to reduce the effect of possible variations in the background values that may be attributed to lithological differences in the sediments or soil [17]. Igeo values divide soil into different quality classes: Class 0 (Igeo $\leq$ 0) uncontaminated; Class 1 (0 < Igeo $\leq$ 1) uncontaminated to moderately contaminated; Class 2 (1 < Igeo $\leq$ 2) moderately contaminated; Class 3 (2 < Igeo $\leq$ 3) moderately to heavily contaminated; Class 4 (3 < Igeo $\leq$ 4) heavily contaminated; Class 5 (4 < Igeo $\leq$ 5) heavily to extremely contaminated; and Class 6 (Igeo > 5) extremely contaminated [15].

2.3.2. Contamination Factor (CF) and Pollution Load Index (PLI)

The contamination factor permits the evaluation of soil pollution by taking into consideration the content of trace elements in the soil and its background values or average shale value [15]. This was calculated using Equation (2):

$$\text{CF} = \text{C sample}/\text{C background} \quad (2)$$

where C sample represents the concentration of an element of interest and C background is the metal background concentration or average the shale value of an element of interest. Consistent with Addo et al. [18], the CF values were categorized into four clusters: CF < 1 (low contamination), 1 ≤ CF < 3 (moderate contamination), 3 ≤ CF ≤ 6 (considerable contamination), and CF > 6 (very high contamination). The PLI was then calculated using the values of CF. This verifies how environmental conditions have deteriorated due to a rise in metal concentration [19], using Equation (3):

$$PLI = \sqrt[n]{(CF1 \times CF2 \times CF3 \times \ldots CFn)} \quad (3)$$

where n represents the number of trace elements detected in this study, and CF connotes the contamination factor computed using Equation (2). According to Kowalska et al. [15], PLI classifies site quality as: 0 < PLI ≤ 1 (unpolluted), 1 < PLI ≤ 2 (moderately to unpolluted), 2 < PLI ≤ 3 (moderately polluted), 3 < PLI ≤ 4 (moderately to highly polluted), 4 < PLI ≤ 5 (highly polluted), and 5 < PLI (very highly polluted).

2.3.3. Enrichment Factors (EF)

The EF was used to differentiate between elements originating from human activities and natural sources [20]. This was computed using Equation (4) by comparing the concentration of an element in a sample with its concentration in the average shale value. Scandium (Sc) was used as the reference element [21].

$$EF = (E/R)\ sample/(E/R)\ background \quad (4)$$

where E is the concentration of an element of interest, R is a reference element of crustal material (Sc), and (E/R) sample is the concentration ratio of E to R in the collected samples, and (E/R) background is the concentration ratio of E to R in the Earth's crust. The EF is categorized into five classes: EF < 2 (depletion to minimal enrichment), EF = 2–5 (moderate enrichment), EF = 5–20 (significant enrichment), EF = 20–40 (very high enrichment), and EF > 40 (extremely high enrichment) [20,21].

2.4. Human Health Risk Assessment of Trace Elements in Road Dust

2.4.1. Non-Cancer Risk Assessment

The average daily dose (ADD) of each analyzed trace element through ingestion, inhalation, and dermal contact was calculated using Equations (5)–(7) [22,23].

$$ADD_{ing} = C \times IngR \times CF \times EF \times ED/BW \times AT \quad (5)$$

$$ADD_{inh} = C \times InhR \times EF \times ED/BW \times AT \times PEF \quad (6)$$

$$ADD_{derm} = C \times SA \times CF \times SL \times ABS \times EF \times ED/BW \times AT \quad (7)$$

where ADD_{ing} signifies the average daily ingestion (mg/kg/day) amount for an element, ADD_{inh} indicates the average daily inhalation (mg/kg/day) amount for an element, and ADD_{derm} specifies the average daily dermal (mg/kg/day) exposure amount of metal, and their values are presented in Table 2. Non-cancer risk was then evaluated from the hazard quotient (HQ) for each trace element by dividing the ADD calculated in Equations (5)–(7) with a particular reference dose (Rfd), using Equation (8):

$$HQ = ADD/RfD \quad (8)$$

HQ > 1 suggests a possibility of health effects, while HQ < 1 shows no possibility of health effects [24]. Furthermore, the hazard index (HI) was then calculated by adding the HQ of the three exposure pathways for a corresponding element [25], using Equation (9):

$$HI = (HQ)\ ing + (HQ)\ inh + (HQ)\ derm \quad (9)$$

A HI value < 1 describes a very low risk, a HI value between 1 and 4 shows that the risk effects are possible, and HI values > 4 describe a high risk [25].

Table 2. Exposure factors for dose models.

Items	Parameter	Meaning	Unit	Value		References
				Children	Adult	
Basic parameter	C	Concentration of a metal	mg/kg	This study	This study	[9,23,26]
	D	Daily dose	mg/kg			[9,23,26]
	CF	Conversion factor	kg/mg	1×10^{-6}	1×10^{-6}	[9,23,26]
Exposure behavioral parameter	ED	Exposure duration	years	6	24	[9,23,26]
	BW	Body weight	kg	15	55.9	[9,23,26]
	EF	Exposure frequency	days/year	350	350	[9,23,26]
	AT	Average time (carcinogen)	days	365×70	365×70	[9,23,26]
		Average time (non-carcinogen)	days	$365 \times$ ED	$365 \times$ ED	[9,23,26]
Digestive tract/inhalation	InhR	Inhalation rate	m^3/kg	5	20	[9,23,26]
	IngR	Ingestion rate	mg/kg	200	100	[9,23,26]
	PEF	Particle emission factor	m^3/kg	1.32×10^9	1.32×10^9	[9,23,26]
Skin contact	SL	Skin adherence factor	mg/cm^2	1	1	[9,23,26]
	SA	Skin surface area	cm^2	1800	5000	[9,23,26]
	ABS	Dermal absorption	-	0.001	0.001	[9,23,26]

2.4.2. Cancer Risk Assessment

The lifetime average daily dose (LADD) of each of the analyzed elements was also calculated for ingestion, inhalation, and dermal exposure pathways, using Equations (10)–(12) [9].

$$LADD_{ing} = C \times CF \times EF/AT \times (IngR_{child} \times ED_{child}/BW_{child} + IngR_{adult} \times ED_{adult}/BW_{adult}) \quad (10)$$

$$LADD_{inh} = C \times EF/AT \times PEF \times (InhR_{child} \times ED_{child}/BW_{child} + InhR_{adult} \times ED_{adult}/BW_{adult}) \quad (11)$$

$$LADD_{derm} = C \times CF \times EF \times SL \times ABS/AT \times (SA_{child} \times ED_{child}/BW_{child} + SA_{adult} \times ED_{adult}/BW_{adult}) \quad (12)$$

where, $LADD_{ing}$ connotes the lifetime average daily ingestion (mg/kg/day) amount of a metal, $LADD_{inh}$ implies the lifetime average daily inhalation (mg/kg/day) amount of an element, and $LADD_{derm}$ indicates the lifetime average daily dermal (mg/kg/day) exposure amount of a metal, and their values are presented in Table 2 [9,23,26–29]. After calculating the LADD of each exposure pathway, a lifetime cancer risk (CR) was then computed by multiplying the LADD with an equivalent slope factor (SF) using Equation (13). The permissible risk usually ranged from 10^{-6} to 10^{-4}: very low ($<10^{-6}$), low (10^{-6}–10^{-5}), medium (10^{-5}–10^{-4}), high (10^{-4}–10^{-3}), and very high ($>10^{-3}$) [30].

$$CR = LADD \times SF \quad (13)$$

2.5. Statistical Methods

The laboratory results were analyzed using Statistical Package for Social Sciences (SPSS) from Microsoft Excel. The data were presented as the minimum, maximum, average mean, and standard deviation. Furthermore, to determine the possible relationship between the elemental concentration and the possible source of origin, Pearson's correlation coefficient and a one way analysis of variance (ANOVA) were adopted.

3. Results and Discussion

3.1. Concentration of Major Elements in Road Dust

The descriptive statistics of major elements is summarized in Table 3, with the average shale values (ASV). The average mean concentrations of SiO_2 and P_2O_5 were higher than their average shale values. A higher silica content may expose the community to serious health implications, such as damaged lung tissue [20]. Its higher concentration in road dust may be associated with its hardness, which makes it difficult to undergo physical weathering [31]. Additionally, the dominance of quartz in road dust may also be linked to the geographical location of the study area, which falls under the Johannesburg dome, which is underlain with sedimentary rocks of the Witwatersrand and Venterdorp Supergroup.

The concentration of P_2O_5, which was also higher than its average shale value, might have been influenced by poor waste management practices in this informal settlement, particularly waste containing phosphate [31]. Runoff from gardens, illegal dumping, and nearby roadside soil polluted by phosphate used in different agricultural activities might have exacerbated the concentration of P_2O_5 in road sediments. Exposure to dust particles containing high concentrations of P_2O_5 may lead to the risk of respiratory distress, and problems of the liver, kidneys, and brain [32].

Furthermore, the average mean concentration of major elements such as Al_2O_3, K_2O, MgO, MnO, and CaO were below their average shale values, suggesting that they are of natural origin and were comparable to the findings of Li et al. [33] in Xi'an city, China. Although these major elements were below their average shale values, their concentrations may possible rise in the near future, due to daily increases in the population and uncontrolled waste generation in this poor informal settlement.

Table 3. Composition of major elements in road dust samples (Wt. %).

Elements	RD01	RD02	RD03	RD04	RD05	Min-Max	Mean	±SD	ASV
Al_2O_3	7.22	8.43	6.21	5.9	6.72	5.9–8.43	6.9	0.99	15.4
CaO	4.23	3.62	1.97	1.09	2.66	1.09–4.23	2.71	1.26	3.1
Fe_2O_3	3.41	3.52	3.68	4.11	4.67	3.41–4.67	3.88	0.52	4.02
K_2O	1.43	2.44	1.27	1.45	1.22	1.22–2.44	1.56	0.5	3.24
MgO	1.18	1.15	0.72	0.32	1.33	0.32–1.33	0.94	0.41	2.44
MnO	0.42	0.24	0.66	1.03	0.51	0.24–1.03	0.57	0.3	trace
Na_2O	0.98	1.89	0.71	0.76	0.62	0.62–1.89	0.99	0.52	1.3
P_2O_5	0.12	0.37	0.11	0.08	0.12	0.08–0.37	0.16	0.12	0.14
SiO_2	69.17	65.37	75.07	79.92	74.25	65.37–79.92	72.76	5.62	58.11
TiO_2	0.36	0.35	0.46	0.35	0.48	0.35–0.48	0.4	0.06	0.65
LOI	11.3	10.52	7.47	4.98	6.61	4.98–11.3	8.18	2.67	-

Notation: LOI = loss on ignition; SD = Standard deviation; ASV = Average shale value; Min = Minimum; Max = Maximum; Average shale value [34].

3.2. Concentration of Trace Elements in Road Dust

The concentration of trace elements presented in Table 4 were ranging as Cr > Ba > Zn > Zr > Sr > V > Rb > Cu > Ni > Pb > Co > Y > Nb > As > Sc > Th > U. Cr, Cu, Zn, Zr, Ba, and Pb were above their average shale values [35], which support the findings of Cai and Li [8] in the street dust of Shijiazhuang, China. When compared with the South African soil screening values [36] for metals in informal settlements only Cr was above this value. This outcome corresponds to the findings of the study conducted by Kamunda et al. [37] in soils from the Witwatersrand Gold Mining Basin, South Africa. The high levels of these trace elements might have been influenced by man-made activities. Dense traffic, which is mostly seen during the early hours and late hours of the day, mostly in tar roads that bisect the settlement, is one of the factors that influence the accumulation of trace elements. Vehicle exhaust is associated with Zr [38], while tire rubber, break wear re-suspended particles, and fuel combustion are sources of Zn [31]. The accumulation of Cu in street dust is associated with brake pad wear [31], while Pb mostly emanated from brake friction, batteries, and gasoline [39].

Table 4. Statistical analysis of trace elements concentration (mg/kg) in road dust samples with average shale values (mg/kg) and South African soil screening values (mg/kg).

Elements	LOD	RD01	RD02	RD03	RD04	RD05	Min-Max	Mean	±SD	ASV	SASSV
As	1	9	10	4	4	9	4–10	7.2	2.9	13	23
Ba	17	563	636	546	729	654	546–729	625.6	73.9	580	n.a
Co	3	16	15	17	20	19	15–20	17.4	2.1	19	300
Cr	4	493	283	694	1088	629	283–1088	637.4	297	90	6.5
Cu	4	125	42	45	43	50	42–125	61	35.9	45	1100
Nb	1	9	8	9	8	9	8–9	8.6	0.5	11	n.a
Ni	4	37	32	53	80	43	32–80	49	19	68	620
Pb	2	32	17	30	41	34	17–41	30.8	8.8	20	110
Rb	2	61	82	59	72	56	56–82	66	10.8	140	n.a
Sc	3	7	8	4	5	5	4–8	5.8	1.6	13	n.a
Sr	2	156	153	99	81	112	81–156	120.2	33.2	300	n.a
Th	3	6	6	5	2.9	3	2.9–6	4.58	1.5	12	n.a
U	3	2.9	2.9	2.9	2.9	2.9	2.9–2.9	2.9	0	3.7	n.a
V	5	57	55	76	75	82	55–82	69	12.2	130	150
Y	1	15	14	14	14	15	14–15	14.4	0.5	26	n.a
Zn	2	700	131	147	67	114	67–700	231.8	263.4	95	9200
Zr	1	164	167	221	172	227	164–227	190.2	31.1	160	n.a

Notation: LOD = limit of detection; RD = road dust; n.a = not available; SD = Standard deviation; ASV = Average shale value; SASSV = South African Soil Screening Value; Min = Minimum; Max = Maximum. Average shale values [35], SASSV [36].

According to Moryani et al. [40], Cr may be released from the combustion of lubricants and fuel. Charcoals is used most of the time in this poor informal settlement for household warming and cooking, and street barbecuing may also distribute Cr around the settlement through fly ash. According to Cui et al. [41], volatile condensing elements such as Cr are enriched in fine fly ash. Unplanned construction in this informal settlement, which occurs most of the time, may also release dust containing Co, possibly from materials containing cobalt, such as alloys and paints [42]. Furthermore, the dumping of waste in any available space or adjacent to the streets may release elements such as Ba. Waste materials such as ceramics, glass, or plastics are considered to be possible sources of Ba [43]. Tires and brakes are also sources of Ba.

When trace elements in road dust were compared with other cities around the world, as shown in Table 5, there were variations in their concentrations. This variation may be attributed to various factors such as a high population, unregulated waste burning, unplanned construction, charcoal burning and the use of firewood, emissions from nearby industrial areas, sewage waste, and poor waste management practices in the settlement. Salah et al. [44] agrees that the accumulation of trace elements in different regions may be influenced by factors such as the type of man-made activities. According to Shi et al. [42], the population level and stages of development may also influence differences in trace element concentration.

3.3. Pollution Assessment and Identification of Sources of Trace Elements in Road Dust

The inclusive Igeo values as presented in Table 6 were as follows: Cr > Zn > Pb > Cu > Zr > Ba > Co > U > Nb > Ni > Y > As > V > Sc > Rb > Sr > Th. Cr was the leading element, indicating possible anthropogenic sources (Figure 3). The possible anthropogenic sources of Cr in this study may be flying ashes from the combustion of charcoal used for indoor warming, cooking, and street barbecuing. Furthermore, the corrosion of vehicular parts, and the combustion of lubricants and fuel are also considered to be sources of Cr [40]. On the basis of the Igeo average values, Cr in this study is an element of concern, and its exposure at high concentrations may trigger serious health implications for the local inhabitants, particularly vulnerable groups such as children, elders, and pregnant women.

Table 5. Comparison of trace elements (mg/kg) in road dust with other global cities.

Trace Elements (mg/kg)	City and Country									
	Ekurhuleni (South Africa)	**Dhaka City (Bangladesh)**	**Tyumen (Russia)**	**Viana do Castelo (Portugal)**	**Barbican Downtown (China)**	**Luanda (Angola)**	**Ahvaz (Iran)**	**Seoul (Korea)**	**Xian (China)**	**Villavicencio (Columbia)**
As	7.2	-	5.7	35	11.7	5	6	24.9	-	-
Ba	625.6	-	317.1	390	748.2	351	-	570	-	-
Co	17.4	-	39.6	-	13.7	2.9	13	17.9	34.1	-
Cr	637.4	-	507.9	210	175.2	26	57	130	175.3	9.4
Cu	61	59.3	57.4	260	50.9	42	45	351	48.9	126.3
Nb	8.6	-	6.6	-	11.9	131	-	-	-	-
Ni	49	-	632.1	16	21	10	58	62	28.3	5.3
Pb	30.8	59.6	33.9	86	93.5	1.7	86	214	97.6	87.5
Rb	66	88.1	27.1	240	44.2	-	-	-	-	-
Sc	5.8	-	10.1	-	-	1.3	-	-	-	-
Sr	120.2	289.9	147.3	190	186.5	172	-	-	-	-
Th	4.6	-	1.9	-	-	1	-	-	-	-
U	2.9	-	1.1	3.6	-	-	-	-	-	-
V	69	-	66.4	15	69.3	20	184	35	55.8	-
Y	14.4	-	7.3	-	18.6	-	-	-	-	-
Zn	231.8	189	160.8	1180	272	317	999	1476	164.9	133.3
Zr	190.2	165.6	60.7	360	120.1	-	-	-	-	-
References	Current study	[45]	[46]	[31]	[33]	[27]	[47]	[48]	[42]	[49]

Table 6. Geo-accumulation (Igeo) values of trace element contamination in road dust.

Igeo Values of Heavy Metals in Road Samples				
Elements	**Min**	**Max**	**Mean**	**Classification**
Cr	0.63	2.42	1.42	Moderately contaminated
Zn	0.14	1.47	0.49	Uncontaminated to moderately contaminated
Pb	0.17	0.41	0.31	Uncontaminated to moderately contaminated
Cu	0.19	0.55	0.27	Uncontaminated to moderately contaminated
Zr	0.12	0.28	0.24	Uncontaminated to moderately contaminated
Ba	0.19	0.24	0.21	Uncontaminated to moderately contaminated
Co	0.16	0.21	0.2	Uncontaminated to moderately contaminated
U	0.16	0.16	0.16	Uncontaminated to moderately contaminated
Nb	0.14	0.16	0.16	Uncontaminated to moderately contaminated
Ni	0.09	0.23	0.14	Uncontaminated to moderately contaminated
Y	0.1	0.11	0.11	Uncontaminated to moderately contaminated
As	0.06	0.15	0.11	Uncontaminated to moderately contaminated
V	0.08	0.13	0.1	Uncontaminated to moderately contaminated
Sc	0.06	0.12	0.09	Uncontaminated to moderately contaminated
Rb	0.08	0.12	0.09	Uncontaminated to moderately contaminated
Sr	0.05	0.1	0.08	Uncontaminated to moderately contaminated
Th	0.05	0.09	0.08	Uncontaminated to moderately contaminated

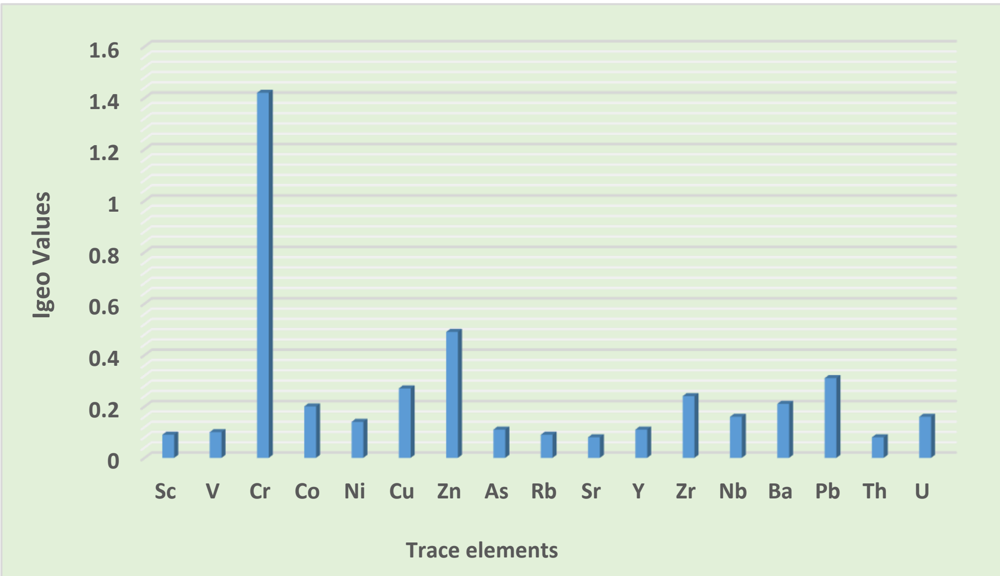

Figure 3. Trace element contamination levels in road dust based on Igeo values.

3.3.1. Contamination Factor (CF) and Pollution Load Index (PLI)

The CF and PLI were adopted to determine the degree of pollution, and to verify how environmental conditions have deteriorated due to the rise in trace element concentrations. The CF average mean value for Cr was above 6, indicating a very high rate of contamination from human activities. This outcome surpasses the findings of Dat et al. [51] for street dust in a metropolitan area of Southern Vietnam, which recorded considerable contamination by Cr. Moderate contamination was noted for elements such as Zn, Pb, Cu, Zr, and Ba, signifying a natural origin with the moderate influence of anthropogenic activities. Similarly, Al-Dabbas et al. [52] also witnessed the moderate contamination of Pb and Zn in the street dust of Diwaniya, Iraq. The majority of trace elements such as Co, U, Nb, Ni, As, Y, V, Rb, Sc, Sr, and Th were classified as having low levels of contamination resembling a natural origin, and this agrees with a study conducted in Bolgatanga Municipality, Ghana [10], which observed a low level of contamination by Co, Ni, and As in road dust, and in the street dust of Diwaniya, Iraq, which was contaminated with a low level of V [52].

As summarized in Table 7, the overall contamination factor values descended in the order of Cr > Zn > Pb > Cu > Zr > Ba > Co > U > Nb > Ni > As > Y > V > Rb > Sc > Sr > Th. As depicted in Figure 4, Cr was the leading pollution contributor amongst trace elements, possibly originating from traffic and charcoal burning, which is practiced daily for household purposes such as indoor warming and cooking. Furthermore, the use of charcoal by street vendors, and emissions from nearby industrial areas, may also be a possible source of Cr. The outcomes of the PLI results showed that road dust was very highly polluted, a similar outcome to the study conducted in the street dust of Ho Chi Minh City, Vietnam [51]. This outcome of PLI may have been influenced by factors such as daily heavy traffic within the study area [31,40,43]. Furthermore, runoff from sewage and uncollected waste materials that lie adjacent to the streets, unregulated waste incineration, and coal fly ashes might also be a contributor to the level of trace elements in road dust. The results of the contamination factor and pollution load index agree with the results of the Igeo accumulation index showing that Cr is an element of public concern in this study, and that remediation and regular monitoring are highly advocated.

Table 7. Contamination factor (CF) and pollution load index (PLI) values of trace elements in road dust.

CFs and PLI Values of Trace Elements in Road Dust Samples				
Elements	**Min**	**Max**	**Mean**	**Classification**
Cr	3.14	12.08	7.08	Very high contamination
Zn	0.7	7.37	2.44	Moderate contamination
Pb	0.85	2.05	1.54	Moderate contamination
Cu	0.93	2.78	1.35	Moderate contamination
Zr	1.02	1.42	1.2	Moderate contamination
Ba	0.94	1.26	1.08	Moderate contamination
Co	0.79	1.05	0.91	Low contamination
U	0.78	0.78	0.8	Low contamination
Nb	0.72	0.81	0.8	Low contamination
Ni	0.47	1.18	0.72	Low contamination
As	0.31	0.77	0.55	Low contamination
Y	0.54	0.58	0.55	Low contamination
V	0.42	0.63	0.53	Low contamination
Rb	0.4	0.58	0.47	Low contamination
Sc	0.31	0.61	0.45	Low contamination
Sr	0.27	0.52	0.4	Low contamination
Th	0.02	0.5	0.38	Low contamination
PLI	0.68	72.9	5.37	Very highly polluted

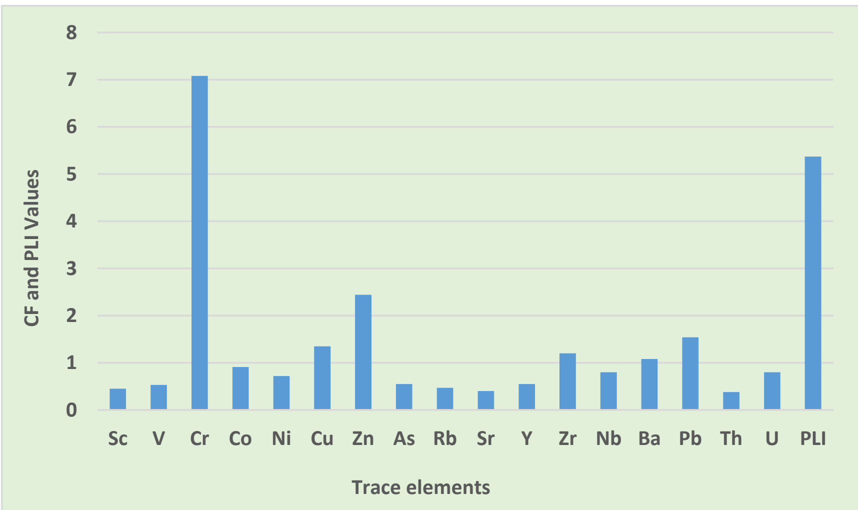

Figure 4. Contamination factor and pollution load index of individual trace elements in road dust.

3.3.2. Enrichment Factor (EF)

To compute the EF values, the average shale values were used as the background concentration, and scandium (Sc) was chosen as a reference metal. The results of EF presented in Table 8 showed Cr to be of significant enrichment, possibly from human activities that matched the findings of the study conducted in the road dust of Katowice and Wroclaw, Poland [53], and they surpassed the findings observed by Cai and Li [8] in the street dust of Shijiazhuang, China, who reported Cr to be of minimal enrichment. Moderate enrichment was reported for Zn, indicating anthropogenic sources. These outcomes are better than the study conducted in Lagos metropolis, Nigeria [54], which observed a very high enrichment of Zn. Other trace elements, Pb, Cu, Zr, Ba, Sc, Co, U, Nb, Ni, Y, As, V, Rb, Sr, and Th were classified as having minimal enrichment, signifying a natural origin, in agreement with the study conducted on the road dust of Dhaka city, Bangladesh [55], which reported Pb, and As to be of minimal enrichment. In the road dust of Bolgatanga Municipality, Ghana, Cu, Zn, Pb, Ni, As, and Co were classified as having minimal enrichment [10]. The geology of the area, the development of the area, the selection of reference materials in calculating EF, and the selection of an element of reference may have an influence on the results of EF [56].

Table 8. Enrichment factor (EF) values of trace elements in road dust.

Elements	EF Average Mean Values	Enrichment Category
Cr	7.08	Significant enrichment
Zn	2.44	Moderate enrichment
Pb	1.54	Minimal enrichment
Cu	1.35	Minimal enrichment
Zr	1.2	Minimal enrichment
Ba	1.08	Minimal enrichment
Sc	1	Minimal enrichment
Co	0.92	Minimal enrichment
U	0.78	Minimal enrichment
Nb	0.78	Minimal enrichment
Ni	0.72	Minimal enrichment
Y	0.55	Minimal enrichment
As	0.55	Minimal enrichment
V	0.53	Minimal enrichment
Rb	0.5	Minimal enrichment
Sr	0.4	Minimal enrichment
Th	0.38	Minimal enrichment

The values of EF were as follows: Cr > Zn > Pb > Cu > Zr > Ba > Sc > Co > U > Nb > Ni > Y > As > V > Rb > Sr > Th. Cr was the major contributor to pollution, followed by Zn, which shows an influence from anthropogenic activities (Figure 5). Human activities such as waste incineration, heavy traffic, poor waste management, coal fly ashes, sewage waste run-off onto the streets, and emissions from nearby industrial areas might be possible anthropogenic sources in this informal settlement. Other researchers also agree that sewage and the incineration of plastics waste may release Zn into urban areas [57], whereas the corrosion of vehicular parts may be the source of Cr [10]. From the results of EF, it can be concluded that the high level of Cr in road dust needs serious attention. Other trace elements were of crustal origin. The natural sources of this trace element may be attributed to the geology of the area, precipitation, or wind-borne soil particles [58].

3.3.3. Pearson Correlation Coefficient Analysis

Pearson's correlation coefficient was performed to establish trace element relationships and to determine their common sources of origin. A correlation matrix of trace elements in road dust samples generated a diverse relationship between the elements. From the correlation analysis in Table 9, a sufficiently high degree of correlation, a moderate degree, and no positive correlation results were observed. A strong correlation was witnessed between pairs of Ni–Cr (0.97), Zn–Cu (r = 0.99), Co–V (r = 0.83), Co–Cr (r = 0.89), Ni–Co (r = 0.81), As–Sc (r = 0.78), Sr–Sc (r = 0.88), Sr–As (r = 0.88), Zr–V (r = 0.81), Pb–Cr (r = 0.89), Pb–Co (r = 0.87), and Pb–Ni (0.77). According to Weissmannova et al. [59], high levels of correlation among trace elements indicates the same sources of pollution, or anthropogenic sources. Therefore, the high degree of correlation between these trace elements in this study is suggestive of the same source of pollution, potentially from anthropogenic activities such as unplanned construction, coal fly ashes, poor waste management, the burning of waste, and dense traffic. Elements such as Zn, Ni, and Cr may be attributed to the burning of fuel [31,40]. Cu and Pb may be associated with brake pad wear and brake friction [31]. Coal burning releases As and Sr [43,45]. Trace elements such as Zr potentially emanate from vehicle exhaust [38], Co from construction materials such as paints [42], and V from oil combustion [43]. Furthermore, the contribution of the concentration of Sc in road dust is understood to be from soil re-suspension, as they are crustal elements [60].

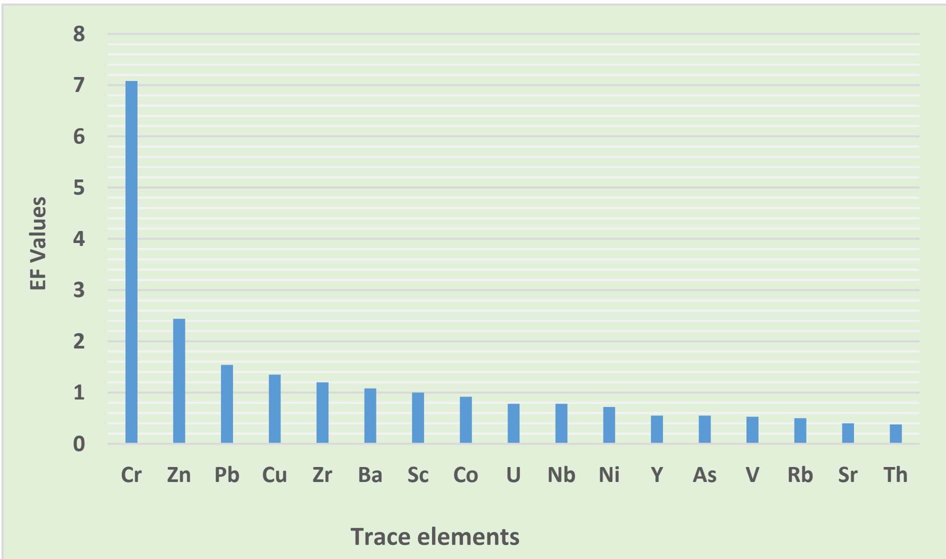

Figure 5. Enrichment factor values of trace elements in road dust.

Table 9. Correlation matrix of trace elements in road dust.

Elements	Sc	V	Cr	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U
Sc	1																
V	−0.91	1															
Cr	−0.72	**0.67**	1														
Co	−0.70	**0.83**	**0.89**	1													
Ni	−0.63	0.56	**0.97**	**0.81**	1												
Cu	0.37	−0.49	−0.27	−0.34	−0.37	1											
Zn	0.42	−0.57	−0.35	−0.46	−0.43	**0.99**	1										
As	**0.78**	−0.55	−0.82	−0.55	−0.86	0.36	0.37	1									
Rb	**0.63**	−0.58	−0.20	−0.32	0.01	−0.33	−0.28	0.16	1								
Sr	**0.88**	−0.85	−0.90	−0.85	−0.89	0.59	**0.65**	**0.85**	0.24	1							
Y	0.11	0.04	−0.23	0.04	−0.43	**0.67**	**0.61**	0.56	−0.63	0.38	1						
Zr	−0.75	**0.81**	0.14	0.36	0.02	−0.40	−0.42	−0.24	−0.70	−0.47	0.16	1					
Nb	−0.39	0.30	−0.15	−0.04	−0.34	0.47	0.46	0.06	−0.93	0.09	**0.67**	**0.61**	1				
Ba	−0.03	0.29	0.54	**0.67**	0.59	−0.48	−0.56	−0.12	0.43	−0.46	−0.21	−0.21	−0.70	1			
Pb	−0.66	**0.65**	**0.89**	**0.87**	**0.77**	0.11	0.00	−0.59	−0.51	−0.70	0.23	0.18	0.19	0.38	1		
Th	**0.66**	−0.86	−0.78	−0.97	−0.70	0.47	0.58	0.42	0.28	0.82	−0.05	−0.44	0.08	−0.71	−0.75	1	
U	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1

Coefficients above 0.6 are in bold.

3.3.4. Statistical Analysis of Trace Elements

A one-way ANOVA was performed to test the difference between the concentrations of elements in road dust samples. The analysis of variance revealed the *p*-value to be 5.09×10^{-20}, as shown in Table 10. The *p*-value was less than the alpha level of 0.05, demonstrating significant differences ($p < 0.05$). This outcome signifies that the trace element pollutants were not from common anthropogenic sources, which is comparable with the study conducted in Yola, Nigeria [61]. In this informal settlement vehicle emissions, re-suspended dust, construction dust, coal fly ashes, emissions from nearby industrial areas, sewage waste, waste burning, or poor waste management may be considered as being possible sources of these trace elements.

Table 10. Single factor analysis of variance (ANOVA) of trace element concentrations in road dust.

Analysis of Variance in Road Dust						
Source of Variation	**SS**	**df**	**MS**	**F**	***p*-Value**	**F Crit**
Between Groups	3,245,171	16	202,823	21	5.09×10^{-20}	1.79
Within Groups	668,540	68	9832			
Total	3,913,712	84				

3.4. Non-Carcinogenic and Carcinogenic Health Risk Assessments of Trace Elements in Road Dust

The health risk assessment of trace element contaminants through various exposure pathways was evaluated by calculating both the non-cancer and the cancer risks for children and adults. The non-cancer risk assessment was calculated with the use of Equations (5)–(9), while cancer risk assessment was computed by using Equations (10)–(13). The non-cancer risk values computed for road dust were based on the reference doses (RfD) in Table 11 and the average daily dose (ADD) values summarized in Table 12. Furthermore, the slope factors in Table 11 and the average daily doses (ADD) in Table 13 were used to assess the lifetime carcinogenic risks of Cr, Ni, As, Pb, and Co in road dust. They were calculated from the average contribution of the individual trace elements in road dust for all of the exposure pathways. The overall health risk assessment of the trace elements in this study does not consider the size of the road dust particles; thus, it uses the dust content as the inhalation amount to determine the general estimation of the health risk assessment. Therefore, the findings of this study signify the utmost likely occurrence of health risks, which also provide data that are valuable for risk cautioning, monitoring, and evading pollution.

Table 11. Reference doses for non-cancer risks and slope factors for cancer risk assessment.

Elements	RfD (mg/kg/d)			SF (mg/kg/d)			References
	RfDing	RfDinh	RfDderm	SFing	SFinh	SFderm	
As	3.00×10^{-4}	3.00×10^{-4}	1.20×10^{-4}	1.50×10^{0}	1.51×10^{1}	3.66×10^{0}	[50,62]
Ba	2.0×10^{-1}	1.43×10^{-4}	4.90×10^{-3}	-	-	-	[27,63]
Co	3.0×10^{-4}	2.00×10^{-2}	5.40×10^{-3}	-	8.40×10^{-1}	-	[23,62–64]
Cr(VI)	3.00×10^{-3}	2.86×10^{-6}	6.00×10^{-5}	5.00×1^{-1}	4.10×10^{-1}	-	[23,50,62]
Cr(III)	1.5	-	-	-	-	-	[63]
Cu	4.00×10^{-2}	4.00×10^{-2}	1.20×10^{-2}	-	-	-	[23,62,65]
Nb	-	-	-	-	-	-	-
Ni	1.1×10^{-2}	6.00×10^{-6}	1.60×10^{-2}	1.70×10^{0}	9.80×10^{0}	-	[23,62,63,65]
Pb	3.50×10^{-3}	3.50×10^{-3}	5.25×10^{-4}	8.50×10^{-3}	4.20×10^{-2}	-	[23,62,63,65]
Rb	-	-	-	-	-	-	-
Sc	-	-	-	-	-	-	-
Sr	6.00×10^{-1}	-	1.20×10^{-1}	-	-	-	[27,63]
Th	-	-	-	-	-	-	-
U	2.0×10^{-4}	-	5.10×10^{-4}	-	-	-	[27,63]
V	5.0×10^{-3}	7.00×10^{-3}	7.00×10^{-3}	-	-	-	[50,62,63]
Y	-	-	-	-	-	-	-
Zn	3.00×10^{-1}	3.00×10^{-1}	6.00×10^{-2}	-	-	-	[23,63,65]
Zr	-	-	-	-	-	-	-

Table 12. Average daily dose (ADD), HQ, and HI values for trace elements in road dust via ingestion, inhalation, and dermal exposure pathways for children and adults.

Pathways	Average Daily Dose (ADD) for Trace Elements in Road Dust (mg/kg/day)																		Total ADD
	Sc	V	CrVI	CrIII	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U	
Children																			
ADDing	7.43×10^{-5}	8.80×10^{-4}	8.10×10^{-3}	8.10×10^{-3}	2.20×10^{-4}	6.30×10^{-4}	7.80×10^{-4}	2.90×10^{-3}	9.20×10^{-5}	8.43×10^{-4}	1.53×10^{-3}	1.84×10^{-4}	2.43×10^{-3}	1.11×10^{-4}	8.00×10^{-3}	3.90×10^{-4}	5.85×10^{-5}	3.70×10^{-5}	3.54×10^{-2}
ADDinh	1.40×10^{-9}	1.70×10^{-8}	1.54×10^{-7}	1.54×10^{-7}	4.21×10^{-9}	1.20×10^{-8}	1.50×10^{-8}	5.61×10^{-8}	1.74×10^{-9}	1.60×10^{-8}	2.91×10^{-8}	3.50×10^{-9}	4.60×10^{-8}	2.08×10^{-9}	1.51×10^{-7}	7.46×10^{-9}	1.10×10^{-9}	7.02×10^{-10}	6.72×10^{-7}
ADDderm	6.67×10^{-9}	7.94×10^{-6}	7.33×10^{-5}	7.33×10^{-5}	2.00×10^{-6}	5.64×10^{-6}	7.02×10^{-6}	2.67×10^{-5}	8.30×10^{-7}	7.59×10^{-6}	1.40×10^{-5}	1.66×10^{-6}	2.20×10^{-6}	9.90×10^{-7}	7.20×10^{-5}	3.54×10^{-6}	5.27×10^{-7}	3.34×10^{-7}	3.00×10^{-4}
ADD	7.43×10^{-5}	8.88×10^{-4}	8.17×10^{-3}	8.17×10^{-3}	2.22×10^{-4}	6.36×10^{-4}	7.87×10^{-4}	2.93×10^{-3}	9.28×10^{-5}	8.51×10^{-4}	1.54×10^{-3}	1.86×10^{-4}	2.43×10^{-3}	1.12×10^{-4}	8.07×10^{-3}	3.94×10^{-4}	5.90×10^{-5}	3.73×10^{-5}	3.57×10^{-2}
Adults																			
ADDing	9.94×10^{-6}	1.20×10^{-4}	1.10×10^{-3}	1.10×10^{-3}	2.98×10^{-5}	8.40×10^{-5}	1.00×10^{-4}	4.00×10^{-4}	1.23×10^{-5}	1.13×10^{-4}	2.06×10^{-4}	2.47×10^{-5}	3.26×10^{-4}	1.47×10^{-5}	1.07×10^{-3}	5.28×10^{-5}	7.86×10^{-6}	4.97×10^{-6}	4.78×10^{-3}
ADDinh	1.50×10^{-9}	1.80×10^{-8}	1.66×10^{-7}	1.66×10^{-7}	4.52×10^{-9}	1.30×10^{-8}	1.60×10^{-8}	6.02×10^{-8}	1.90×10^{-9}	1.71×10^{-8}	3.12×10^{-8}	3.74×10^{-9}	4.94×10^{-8}	2.23×10^{-9}	1.62×10^{-7}	8.00×10^{-9}	1.20×10^{-9}	7.54×10^{-10}	7.23×10^{-7}
ADDderm	4.97×10^{-7}	5.92×10^{-6}	5.50×10^{-5}	5.50×10^{-5}	1.49×10^{-6}	4.20×10^{-6}	5.23×10^{-6}	1.99×10^{-5}	6.17×10^{-7}	5.66×10^{-6}	1.03×10^{-5}	1.23×10^{-6}	1.63×10^{-5}	7.40×10^{-7}	5.40×10^{-5}	2.64×10^{-6}	3.93×10^{-7}	2.49×10^{-7}	2.39×10^{-4}
ADD	1.04×10^{-5}	1.26×10^{-4}	1.16×10^{-3}	1.16×10^{-3}	3.13×10^{-5}	8.82×10^{-5}	1.05×10^{-4}	4.20×10^{-4}	1.29×10^{-5}	1.19×10^{-4}	2.16×10^{-4}	2.59×10^{-5}	3.42×10^{-4}	1.54×10^{-5}	1.12×10^{-3}	5.54×10^{-5}	8.25×10^{-6}	5.22×10^{-6}	5.02×10^{-3}
Pathways	**Non−cancer risk values for trace elements in road dust (mg/kg/day)**																		**Total HI**
Children																			
HQing	-	1.80×10^{-1}	2.70×10^{0}	5.40×10^{-3}	7.30×10^{-1}	6.00×10^{-3}	1.95×10^{-2}	9.67×10^{-3}	3.06×10^{-1}	-	2.55×10^{-3}	-	-	-	4.00×10^{-2}	1.11×10^{-1}	-	1.90×10^{-1}	4.30×10^{0}
HQinh	-	2.43×10^{-6}	5.38×10^{-2}	-	2.10×10^{-7}	2.00×10^{-3}	3.75×10^{-7}	1.87×10^{-7}	5.80×10^{-6}	-	-	-	-	-	1.05×10^{-3}	2.13×10^{-6}	-	-	5.69×10^{-2}
HQderm	-	1.13×10^{-3}	1.22×10^{0}	-	3.70×10^{-4}	3.52×10^{-4}	5.85×10^{-4}	4.45×10^{-4}	6.92×10^{-3}	-	-	-	-	-	1.47×10^{-2}	6.74×10^{-3}	-	6.55×10^{-4}	1.25×10^{0}
HI	-	1.81×10^{-1}	3.97×10^{0}	5.40×10^{-3}	7.30×10^{-1}	8.35×10^{-3}	2.01×10^{-2}	1.01×10^{-2}	3.13×10^{-1}	-	2.55×10^{-3}	-	-	-	5.58×10^{-2}	1.18×10^{-1}	-	1.91×10^{-1}	5.61×10^{0}
Adults																			
HQing	-	2.40×10^{-2}	3.67×10^{-1}	7.30×10^{-4}	1.49×10^{-3}	8.00×10^{-4}	2.50×10^{-3}	1.33×10^{-3}	4.10×10^{-2}	-	3.43×10^{-3}	-	-	-	2.00×10^{-2}	1.51×10^{-2}	-	2.50×10^{-2}	5.02×10^{-1}
HQinh	-	2.57×10^{-6}	5.80×10^{-2}	-	2.26×10^{-7}	2.17×10^{-3}	4.00×10^{-7}	2.01×10^{-7}	6.33×10^{-6}	-	–	-	-	-	1.13×10^{-3}	2.28×10^{-6}	-	-	6.13×10^{-2}
HQderm	-	8.46×10^{-4}	9.17×10^{-1}	-	2.76×10^{-4}	2.62×10^{-4}	4.36×10^{-4}	3.32×10^{-4}	5.14×10^{-3}	-	8.58×10^{-5}	-	-	-	1.10×10^{-2}	5.03×10^{-3}	-	4.88×10^{-4}	9.41×10^{-1}
HI	-	2.48×10^{-2}	1.34×10^{0}	7.30×10^{-4}	1.77×10^{-3}	3.23×10^{-3}	2.94×10^{-3}	1.66×10^{-3}	4.61×10^{-2}	-	3.52×10^{-3}	-	-	-	3.21×10^{-2}	2.01×10^{-2}	-	2.55×10^{-2}	1.50×10^{0}

Table 13. Carcinogenic average daily dose (ADD) for trace elements in road dust via ingestion, inhalation, and dermal exposure pathways for children and adults.

Pathways	Cancer Average Daily Dose (ADD) for Trace Elements in Road Dust (mg/kg/day)																		Total ADD
	Sc	V	CrVI	CrIII	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th	U	
Children																			
ADDing	7.43×10^{-5}	8.80×10^{-4}	8.10×10^{-3}	8.10×10^{-3}	2.20×10^{-4}	6.30×10^{-4}	7.80×10^{-4}	2.90×10^{-3}	9.20×10^{-5}	8.43×10^{-4}	1.53×10^{-3}	1.84×10^{-4}	2.43×10^{-3}	1.11×10^{-4}	8.00×10^{-3}	3.90×10^{-4}	5.85×10^{-5}	3.70×10^{-5}	3.54×10^{-2}
ADDinh	1.40×10^{-9}	1.70×10^{-8}	1.54×10^{-7}	1.54×10^{-7}	4.21×10^{-9}	1.20×10^{-8}	1.50×10^{-8}	5.61×10^{-8}	1.74×10^{-9}	1.60×10^{-8}	2.91×10^{-8}	3.50×10^{-9}	4.60×10^{-8}	2.09×10^{-9}	1.51×10^{-7}	7.46×10^{-9}	1.10×10^{-9}	7.02×10^{-10}	6.72×10^{-7}
ADDderm	6.67×10^{-9}	7.94×10^{-6}	7.33×10^{-5}	7.33×10^{-5}	2.00×10^{-6}	5.64×10^{-6}	7.02×10^{-6}	2.67×10^{-5}	8.30×10^{-7}	7.59×10^{-6}	1.40×10^{-5}	1.66×10^{-6}	2.20×10^{-6}	9.90×10^{-7}	7.20×10^{-5}	3.54×10^{-6}	5.27×10^{-7}	3.34×10^{-7}	3.00×10^{-4}
Total	7.43×10^{-5}	8.88×10^{-4}	8.17×10^{-3}	8.17×10^{-3}	2.22×10^{-4}	6.36×10^{-4}	7.87×10^{-4}	2.93×10^{-3}	9.28×10^{-5}	8.51×10^{-4}	1.54×10^{-3}	1.86×10^{-4}	2.43×10^{-3}	1.12×10^{-4}	8.07×10^{-3}	3.94×10^{-4}	5.90×10^{-5}	3.73×10^{-5}	3.57×10^{-2}
Adults																			
ADDing	9.94×10^{-6}	1.20×10^{-4}	1.10×10^{-3}	1.10×10^{-3}	2.98×10^{-5}	8.40×10^{-5}	1.00×10^{-4}	4.00×10^{-4}	1.23×10^{-5}	1.13×10^{-4}	2.06×10^{-4}	2.47×10^{-5}	3.26×10^{-4}	1.47×10^{-5}	1.07×10^{-3}	5.28×10^{-5}	7.86×10^{-6}	4.97×10^{-6}	4.78×10^{-3}
ADDinh	1.50×10^{-9}	1.80×10^{-8}	1.66×10^{-7}	1.66×10^{-7}	4.52×10^{-9}	1.30×10^{-8}	1.60×10^{-8}	6.02×10^{-8}	1.90×10^{-9}	1.71×10^{-8}	3.12×10^{-8}	3.74×10^{-9}	4.94×10^{-8}	2.23×10^{-9}	1.62×10^{-7}	8.00×10^{-9}	1.20×10^{-9}	7.54×10^{-10}	7.23×10^{-7}
ADDderm	4.97×10^{-7}	5.92×10^{-6}	5.50×10^{-5}	5.50×10^{-5}	1.49×10^{-6}	4.20×10^{-6}	5.23×10^{-6}	1.99×10^{-5}	6.17×10^{-7}	5.66×10^{-6}	1.03×10^{-5}	1.23×10^{-6}	1.63×10^{-5}	7.40×10^{-7}	5.40×10^{-5}	2.64×10^{-6}	3.93×10^{-7}	2.49×10^{-7}	2.39×10^{-4}
Total	1.04×10^{-5}	1.26×10^{-4}	1.16×10^{-3}	1.16×10^{-3}	3.13×10^{-5}	8.82×10^{-5}	1.05×10^{-4}	4.20×10^{-4}	1.29×10^{-5}	1.19×10^{-4}	2.16×10^{-4}	$2.59 \times 10–5$	3.42×10^{-4}	1.54×10^{-5}	1.12×10^{-3}	5.54×10^{-5}	8.25×10^{-6}	5.22×10^{-6}	5.02×10^{-3}
LADD	8.47×10^{-5}	1.01×10^{-3}	9.33×10^{-3}	9.33×10^{-3}	2.53×10^{-4}	7.24×10^{-4}	8.92×10^{-4}	3.35×10^{-3}	1.06×10^{-4}	9.69×10^{-4}	1.76×10^{-3}	2.12×10^{-4}	2.77×10^{-3}	1.27×10^{-4}	9.20×10^{-3}	4.49×10^{-4}	6.73×10^{-5}	4.26×10^{-5}	4.07×10^{-2}

3.4.1. Non-Carcinogenic Risk Assessment

The total HI value in the population of children exhibited a possibility for non-carcinogenic risk (Table 12). This was driven greatly by ingestion and dermal pathways with the likelihood of non-carcinogenic risk. As shown in Figure 6, the total HI values through various exposure pathways in descending order were ingestion > dermal > inhalation, while the contribution of individual elements to the total HI was, in order, Cr(VI) > Co > As > U > V > Pb > Ba > Cu > Zn > Ni > Cr(III) > Sr (Figure 7). The discoveries of this study are similar to the findings of the studies conducted in the road dust of Viano do Castelo, Portugal [31], in Wroclaw and Katowice, Poland [53], the urbanized cities of Pakistan [9], and in Lagos metropolis, Nigeria [54].

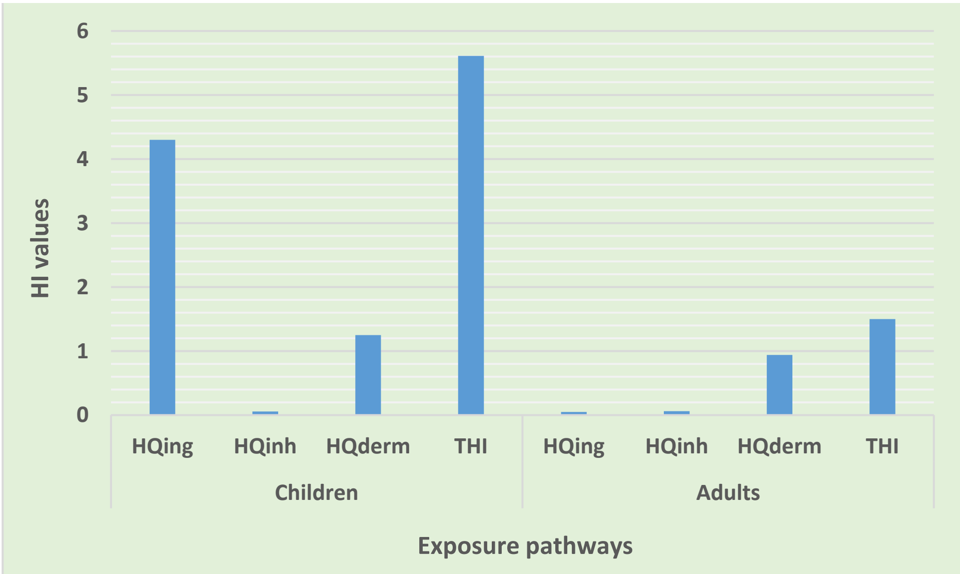

Figure 6. Hazard index for exposure to trace elements via various pathways.

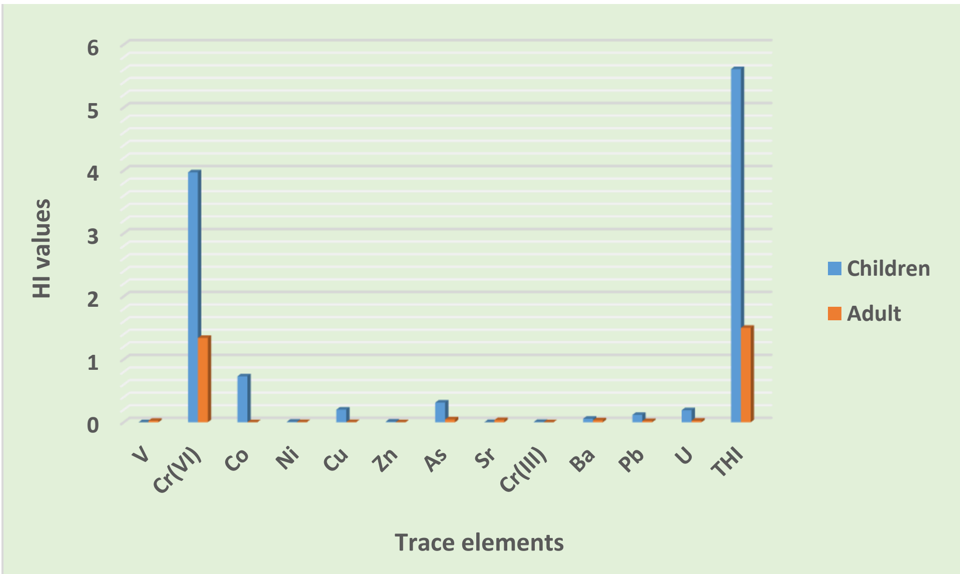

Figure 7. Contribution of trace elements to non-carcinogenic risk.

Chromium (Cr VI) was the only element that presented a probability for non-cancer risk. Taiwo et al. [54] in Lagos metropolis, Nigeria also reported Cr as being the principal contributor to non-cancer risk in road dust, which supports the findings of this study. The outcomes of this study suggest that the children group in this informal settlement are at risk of non-carcinogenic cancer, mainly through ingestion and dermal exposure, which is a concern, considering that they have a custom of playing in the dust and sucking their fingers or hands while playing. Children may be exposed to Cr mainly through inhalation and dermal contact, as it is the only element with the possibility of non-cancer risk. Other elements and inhalation pathways showed no possibility of non-cancer risk.

In the adult population, the total HI value showed a likelihood of causing non-carcinogenic risks. All exposure pathways had no chance for causing non-carcinogenic risks, and their trends were in the order of dermal > ingestion > inhalation (Figure 6). There was also no possibility of non-cancer risk from all of the trace elements, except from Cr (VI). Their contributions to the total hazard index were as follows: Cr(VI) > As > Ba > U > V > Pb > Sr > Ni > Cu > Co > Zn > Cr(III) (Figure 7). In adults, dermal contact was the major contributor to non-cancer risk, which makes re-suspended particles a serious concern. Exposure to Cr through dermal contact may lead to the possibility of non-cancer risks among adults in this poor informal settlement. The overall level of trace elements in road dust in this informal settlement showed the possibility of non-cancer risks to the local inhabitants. Additionally, the total HI value in the children population was higher than the total HI value in the adult population, evidencing the high possibility for heavy metals to cause non-cancer risks to children compared to the adult population (Figure 6). Similar outcomes were reported by Qadeer et al. [9] in urbanized cities of Pakistan, and by Candeias et al. [31] in Viano do Castelo, Portugal.

3.4.2. Carcinogenic Risk (CR) Assessment

The results of the cancer risk assessment, as summarized in Table 14, revealed that the total CR values in children and adults were between 10^{-4} and 10^{-3}. Children were at a higher risk than adults. Furthermore, the lifetime cancer risk value for the entire population was also between 10^{-4} and 10^{-3}. This value is considered to be a high risk, suggesting a concern for the residents regarding the possible CR of trace elements in road dust. Only the ingestion pathway exhibited the probability for cancer risk to both children and adults. The total cancer risks through various exposure pathways were as follows: ingestion > dermal > inhalation and ingestion > dermal > inhalation, for both children and adults, respectively (Figure 8).

Table 14. Cancer risk assessment for trace elements in road dust via ingestion, inhalation, and dermal exposure pathways for children and adults.

Pathways	Cancer Risk Values for Trace Elements in Road Dust (mg/kg/day)					Total CR
	Cr	Co	Ni	As	Pb	
			Children			
CRing	3.54×10^{-4}	-	3.60×10^{-5}	1.18×10^{-5}	2.86×10^{-7}	4.02×10^{-4}
CRinh	5.41×10^{-9}	3.03×10^{-10}	9.99×10^{-9}	2.26×10^{-10}	2.68×10^{-11}	1.60×10^{-8}
CRderm	-	-	-	2.59×10^{-7}	-	2.59×10^{-7}
CR	3.54×10^{-4}	3.03×10^{-10}	3.60×10^{-5}	1.21×10^{-5}	2.86×10^{-7}	4.02×10^{-4}
			Adults			
CRing	1.87×10^{-4}	-	1.90×10^{-5}	6.34×10^{-6}	1.54×10^{-7}	2.12×10^{-4}
CRinh	2.33×10^{-8}	1.30×10^{-9}	4.28×10^{-8}	9.69×10^{-10}	1.15×10^{-10}	6.85×10^{-8}
CRderm	-	-	-	7.76×10^{-7}	-	7.76×10^{-7}
CR	1.87×10^{-4}	1.30×10^{-9}	1.90×10^{-5}	7.12×10^{-6}	1.54×10^{-7}	2.13×10^{-4}
LCR	5.41×10^{-4}	1.60×10^{-9}	5.51×10^{-5}	1.92×10^{-5}	4.40×10^{-7}	6.16×10^{-4}

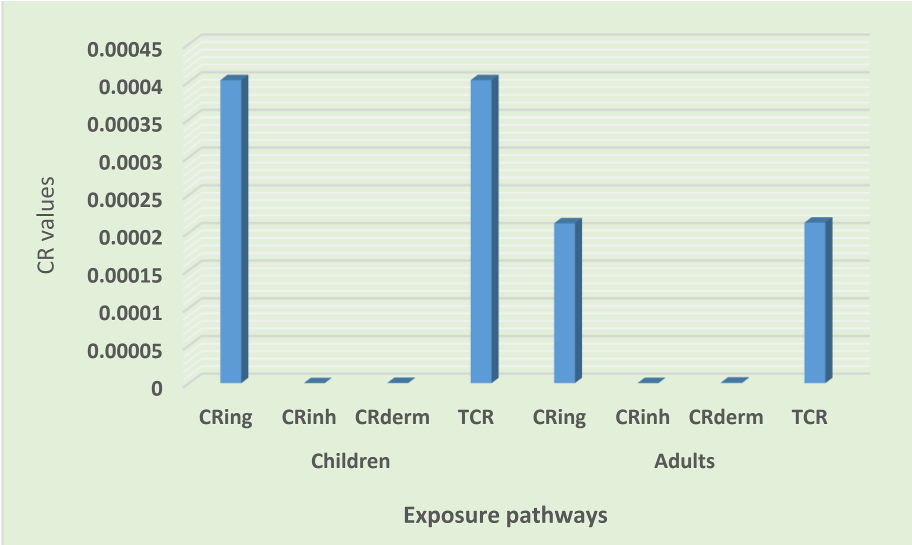

Figure 8. Contribution of exposure pathway carcinogenic risks.

Furthermore, all of the trace element cancer risks values were within the acceptable limit in both the children and adult groups, except for the Cr risk value. The CR values of all of the elements were as follows: Cr > Ni > As > Pb > Co and Cr > Ni > As > Pb > Co for children and adults, respectively (Figure 9. According to various researchers, including Qadeer et al. [9] in the urbanized cities of Pakistan, and Candeias et al. [31] in Viano do Castelo, Portugal, the ingestion of road dust in the children group was the leading contributor to cancer risk, which is comparable to the outcomes of this study. Similar findings confirming Cr to be the main driver of carcinogenic risk were also reported by Dat et al. [51] in the street dust of a metropolitan area in Southern Vietnam. Similarly, Dat et al. [51], for the street dust of a metropolitan area in Southern Vietnam, and Taiwo et al. [54], for Lagos metropolis, Nigeria, elucidated the ingestion pathway and determined Cr as being the leading contributor to the total cancer risk among adults. From the results of the cancer risk assessment, it was clear that trace elements in road dust had the possibility for contributing to lifetime carcinogenic risks for the entire population, and Cr was the leading contributor (Figure 10). Children were at a high risk of cancer compared to the adult group (Figure 9). The community should be educated on the importance of the environment, pollution, waste management, and health. Remediation, cleaning, and the regular monitoring of heavy metals is desirable for the safety of the inhabitants and the sustainability of the settlement.

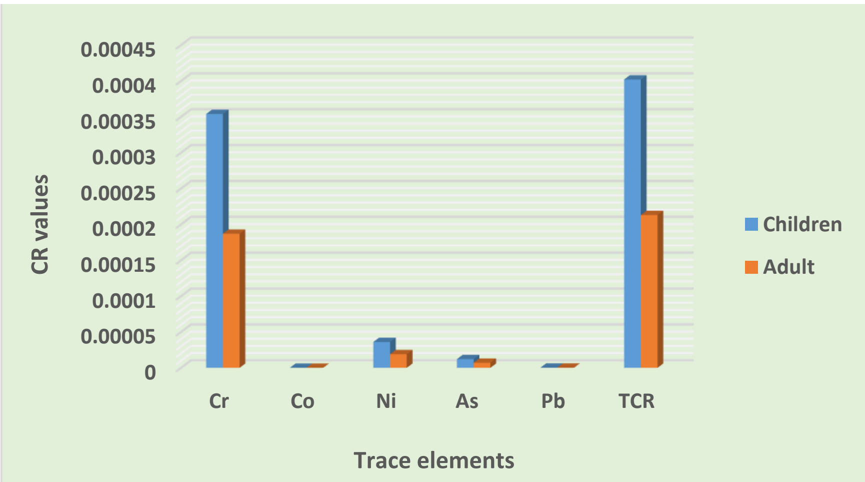

Figure 9. Contribution of trace elements to cancer risks.

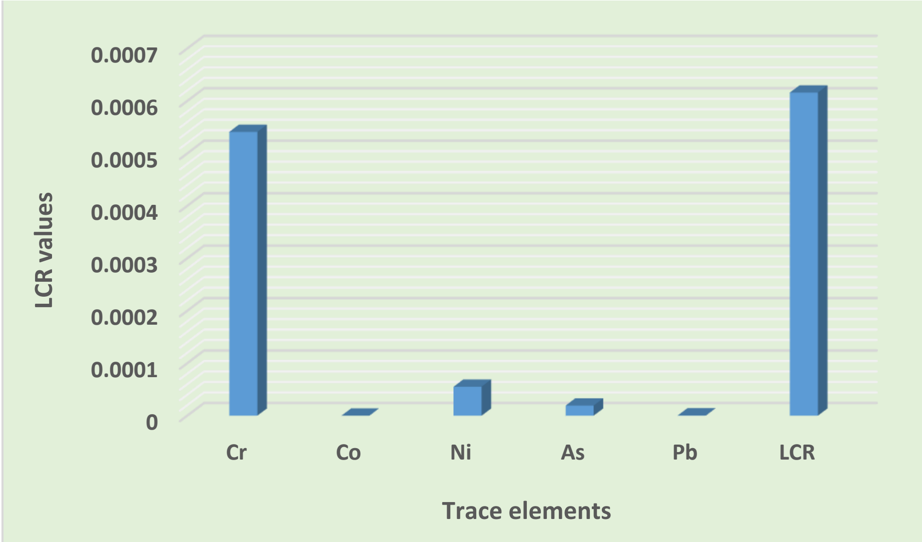

Figure 10. Contribution of trace elements to lifetime carcinogenic risks.

3.5. Health Implications Associated with Trace Elements Exposure in Road Dust

Among the examined elements, only six trace elements were above their average shale values, which is a health concern for the local population, particularly children. As reported by Jin et al. [66], outdoor play areas represent important exposure situations for children in many urban settlement areas. Hassaan et al. [57], stated that trace elements at high concentrations are toxic. The toxicity of trace elements in this study can be listed as Cr > Ba > Zn > Zr > Cu > Pb, and their exposure may lead to serious health implications to the local inhabitants. Cr may trigger liver disorder and irritation [11]. Barium (Ba) may lead to renal failure and lung sclerosis [67]. Exposure to zinc (Zn) may cause risks of prostate cancer, and exhaustion [12]. Zirconium (Zr) may lead to pulmonary effects and hoarseness [68]. Copper (Cu) is associated with dizziness and stomach cramps [12]. Furthermore, exposure to lead (Pb) may cause hormonal changes and reduced potency in males [69].

4. Conclusions

This study was aimed at determining the influence of urban informal settlements on trace element accumulation in road dust from Ekurhuleni Metropolitan Municipality, South Africa, and their health implications. The outcomes of the study have revealed that informal settlement activities have considerable influences on the accumulation of trace elements in road dust during the winter season. In this poor informal settlement, major elements (SiO_2 and P_2O_5) and trace elements (Cr, Cu, Zn, Zr, Ba, and Pb) were particular health concerns as they were above their corresponding average shale values. In particular, Cr was a major health concern to the inhabitants, as its level of accumulation in the road dust was high. Furthermore, the level of trace elements in road dust exhibited a possibility for non-cancer risks and cancer risks to the entire population, and Cr was the major driver for both non-carcinogenic and carcinogenic risks for the entire population. Cleaning and the regular monitoring of heavy metals in poor urban informal settlements is desirable for the safety of the inhabitants and the sustainability of the settlement. The study will provide valuable scientific data on urban informal settlement geochemistry and health risks, which will be used as a reference value and for remediation measures. The overall health risk assessment of trace elements in this study did not take into account the size of the road dust particles; thus, future work should cover the variation in particle size distribution and morphology over different seasons of the year.

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Data Availability Statement: The raw data utilized in this study are obtainable upon request from the corresponding author.

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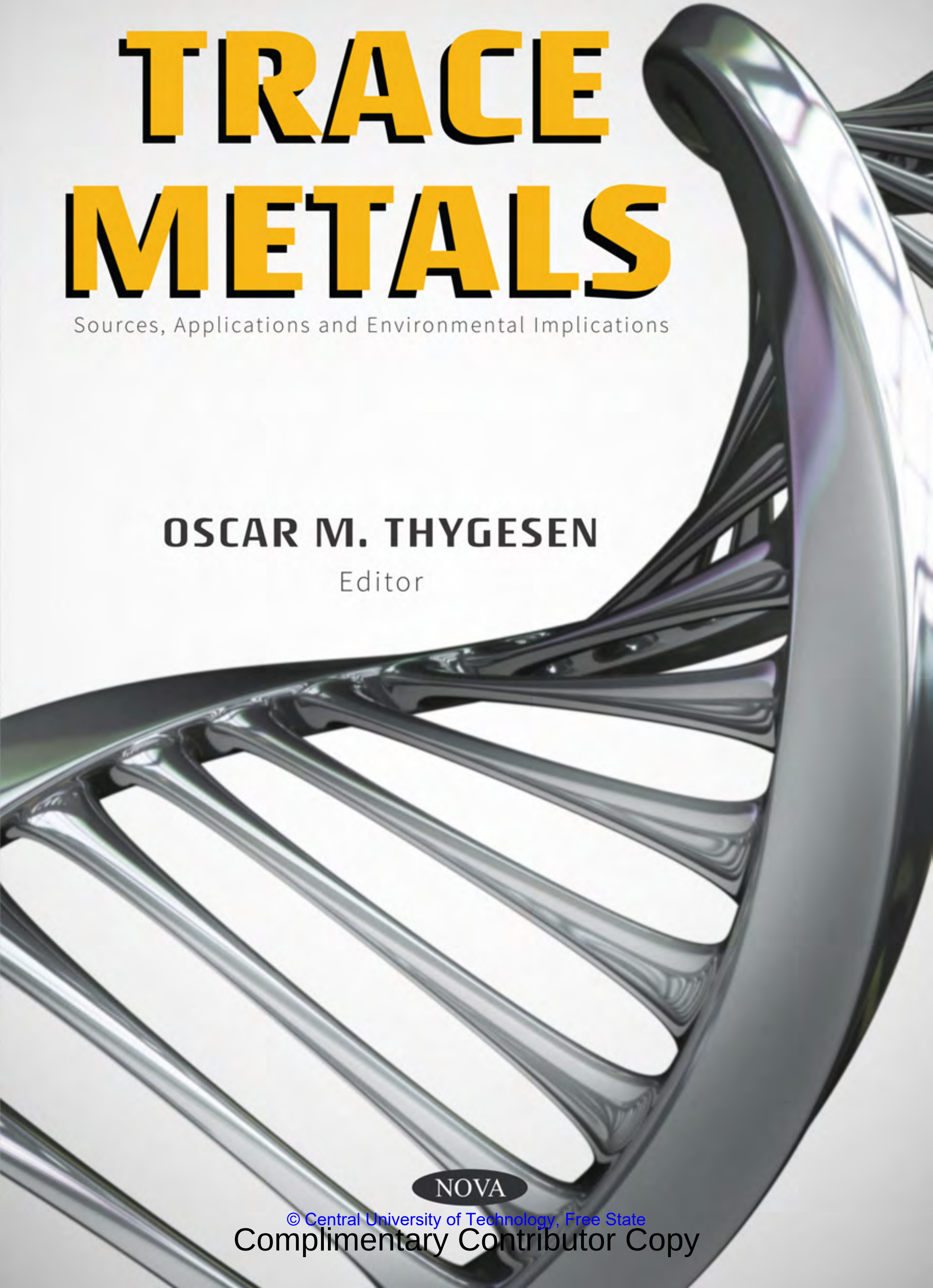

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Contents

Preface

Trace metals are necessary for the proper functioning of living organisms and are absorbed by the body through diet or environmental exposure. However, excessive intake of trace metals can cause health problems. As such, the study of the presence of trace metals in the environment and their effects on health is important. This volume includes four chapters that provide details about trace metals in various contexts. Chapter One explains the nutritional zinc requirements of humans and discusses the usefulness of different supplements in various applications. Chapter Two addresses the different aspects of metal-microbial interactions, focusing on soil and sediment ecosystems. Chapter Three addresses pollution of heavy metals, emission sources, health implications, and commonly used methods for assessment of pollution. Lastly, Chapter Four assesses possible changes in the geochemical behavior of chromium caused by sediment resuspension in a hypereutrophic estuary that receives domestic and industrial effluents daily.

Chapter 1 - Iron, zinc, copper, manganese, molybdenum, cobalt, and possibly, chromium are essential trace metals for humans. Zinc, in particular, is vital for many physiological processes that regulate endocrine and immune functions and control healthy brain development and activity. However, currently, it is estimated that 20 percent of the human population is at risk of zinc deficiency. Therefore, zinc supplementation became a significant focus in trace metal and health research, acting as a nutritional supplement to compensate for low zinc bioavailability and nutraceutical with pharmacological activity. This chapter will provide background to the nutritional zinc requirements of humans, introduce zinc supplements such as inorganic and organic supplements and discuss their differences and usefulness in various applications. In addition, the chapter will summarize scientifically proven beneficial effects of zinc supplementation and highlight new potential areas for zinc supplementation as a prevention and treatment strategy.

Chapter 2 - Modern globalisation has escalated the sources of heavy metal pollution in human-centered natural habitats. Heavy metals are persistent and are toxic to all forms of life. So, metal detoxification and restoration of metal-contaminated sites are very significant. Detoxification with microbes is very relevant as it is a cost-effective and natural method. Microorganisms living in already contaminated environments are often well adapted to survive in the presence of existing contamination. Microorganisms like algae, bacteria, and fungi can detoxify trace metals by bioremediation. Many reports on metal-microbe interactions highlight its important role in eradicating heavy metals from the ecosystem in an eco-friendly way through removal, detoxification, and recovery of organic and inorganic metals. There is a long quandary on how microbes link with metals in both natural and manmade environmental or biogeochemical cycling of metals by microorganisms. This chapter, therefore, attempts to address the different aspects of metal-microbial interactions, focusing on soil and sediment ecosystems.

Chapter 3 - With the rapid industrialization and economic development, heavy metals are continuing to be introduced to soils and sediments through fertilization, irrigation, rivers, runoff, atmospheric deposition and point sources. Additionally, activities such as metal mining, refining, and refinishing by products also contribute to the introduction of heavy metals in the environment. All these activities decrease the capability of the environment to support life thus threatening people, animal and plant health. Health implications associated with heavy metal exposure include those that disturbs nervous, blood forming, cardiovascular, renal and reproductive systems. Furthermore, accumulation of heavy metals in soil diminish quality of soil, cause crop yield decrease and affect the quality of agricultural products. It is important to appraise the concentration of heavy metals in the environment as they are toxic, persistent and non-degradable. Pollution indices are effective in appraisal of soil pollution with heavy metals, monitoring quality of soil and ensuring future sustainability. This chapter seeks to address the pollution of heavy metals, emission source, health implications and commonly used methods for assessment of pollution and for health risks assessment.

Chapter 4 - The resuspension of contaminated sediments in the water column has been recognized as an important process of metal pollutants remobilization in historically contaminated estuaries, which can change the concentration and bioavailability of these elements. The aim of this study was to assess possible changes on the geochemical behavior of chromium (Cr) caused by sediment resuspension in the area of a hypereutrophic estuary

(Guanabara Bay, Brazil) that receives domestic and industrial effluents daily during the recent decades. This study evaluated bioavailability change (BC) for Cr in estuarine sediments from Iguaçu River (located within the most impacted Guanabara Bay area), in response to laboratorial sediment resuspension experiments. The responses of sediments layers from different depth intervals were compared, since dredging activities usually promote resuspension of sediments removed from variable depths. Performed evaluations on the anthropogenic interference on sediment quality also included ecological risk index ($E^i f$) estimates. Chromium concentrations obtained using a weak acid extraction (in a 1 mol L^{-1} HCl solution) were considered as the reactive (bioavailable) Cr phase. After resuspension along different time intervals, the uppermost sediment layers showed higher Cr concentrations in comparison with the non-resuspended control sediment. Some were above the Effect Range Low (ERL) sediment quality guideline, suggesting risks of adverse biological effects. These findings indicate increased potential bioavailability of the metal after resuspension. The $E^i f$ indicated low risk for Cr in all depth interval. The combined use of risk indices can be a useful tool for a more adequate management of dredging activities, helping in the prediction of contamination risks.

Chapter 3

Heavy Metal Pollution and Public Health: A Review of Heavy Metal Pollution, Health Implications, and Methods Potentially Used for Pollution Assessment

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Abstract

With the rapid industrialization and economic development, heavy metals are continuing to be introduced to soils and sediments through fertilization, irrigation, rivers, runoff, atmospheric deposition and point sources. Additionally, activities such as metal mining, refining, and refinishing by products also contribute to the introduction of heavy metals in the environment. All these activities decrease the capability of the environment to support life thus threatening people, animal and plant health. Health implications associated with heavy metal exposure include those that disturbs nervous, blood forming, cardiovascular, renal and reproductive systems. Furthermore, accumulation of heavy metals in soil diminish quality of soil, cause crop yield decrease and affect the quality

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of agricultural products. It is important to appraise the concentration of heavy metals in the environment as they are toxic, persistent and non-degradable. Pollution indices are effective in appraisal of soil pollution with heavy metals, monitoring quality of soil and ensuring future sustainability. This chapter seeks to address the pollution of heavy metals, emission source, health implications and commonly used methods for assessment of pollution and for health risks assessment.

Keywords: heavy metal pollution, public health, anthropogenic, health implications, pollution index, enrichment factor

Introduction

Heavy Metal Pollution and Public Health

The area where living (people, animals and plants) and non-living organisms (soil, water and air) live is referred to as the environment. The environment is clearly distinguished by the biosphere, atmosphere, lithosphere and hydrosphere. The biosphere is considered to be important as it is the area where living organisms intermingle with each other and the non-living organisms (Masindi and Muedi, 2018). Industrialisation and globalisation have damaged environment and their capability to nurture life. Moreover, they have presented environmental contaminants that disturb the overall operation of environment (Sands, 2003; Masindi and Muedi, 2018). Environmental contaminants are chemicals that are available at high concentration than in any fragment of the environment (Martin and Johnson, 2012; Masindi and Muedi, 2018; Briffa, et al., 2020).

The world has experienced an increasing ecological and global public health associated with environmental contamination by heavy metals (Tchounwou et al., 2014). Concerns about the accumulation of heavy metals in soils are due to its persistence and potential toxicity (Ferreira Baptista and De Miguel, 2005; Gabarron, et al., 2017). Heavy metals in the environment occur as a result of natural activities, mining activities, industrial activities, agricultural activities, domestic effluents, pharmaceutical and atmospheric sources. Increase usage of heavy metals in some industrial, agricultural, domestic and technological applications has also increased human exposure to heavy metals (He, et al., 2005; Tchounwou, et al., 2014).

In general, high concentration of heavy metals in the environment result in health complications that disturb nervous, blood forming, cardiovascular, renal and reproductive systems. The medical implications of exposure to heavy metals pollution are reduced intelligence; loss of attention and abnormal behaviour; and cardiovascular disease in adults (Jarup, 2003; Timothy and Williams, 2019). Human exposure to heavy metals may occurs through three primary routes namely, inhalation, ingestion and skin absorption (Davis and Mundalamo, 2010).

Contamination by heavy metals may change the chemical composition of plants and thus affect the quality and effectiveness of medicinal plant species to produce organic products. Toxicity of heavy metal can damage the root system, disturb plants growth, enzymatic activity, stoma functions, photosynthesis activity and accumulation of other nutrient elements (Abrahams, 2002; Timothy and Williams, 2019). High concentration of heavy metals in soil can also diminish quality of soil, cause crop yield decrease and affect the quality of agricultural products and consequently affect people, animals and ecosystem health negatively (Nagajyoti, et al., 2010; Hu, et al., 2013; Timothy and Williams, 2019).

Heavy metals proliferation in body fatty tissues may affect human central nervous system as they are non- degradable and toxic in high concentration (Denier, et al., 2009; Ghanavati, et al., 2019; Kianpor, et al., 2019). It is important to monitor the concentration of heavy metals in the environment as they are toxic, persistent and non-degradable (Timothy and Williams, 2019). In order to assess the pollution level of heavy metals in the natural environmental samples such as soil, dust, water, etc. and determine their sources, pollution indices or methods are very useful (Othman, et al., 2019; Ghanavati, 2019; Kianpor, et al., 2019). This chapter provides an analysis of the heavy metal pollution of major public concern, their ways to environment, health implications and potentially used methods for pollution assessment and risk assessment.

Method

The information was gathered from the online peer reviewed journals, student papers, and books mainly from PubMed, MDPI, WHO, Research gate, Science direct, or Springer. This were peer reviewed journals, student papers and books published from 1969 to 2021. Only papers related to this chapter and published in English were scrutinized and utilised. Consideration of literature was based mainly on published articles with focus on heavy metal pollution, health implications, and potential used methods for pollution assessment around the world.

Results and Discussion

After thorough perusal of published manuscripts, student papers and books, only studies focusing on heavy metal pollution and public health were selected. The high percentage of manuscripts were concentrated on pollution and health risk assessment of heavy metals in urban environment. Some of the reviewed relevant concepts are discussed underneath here.

Heavy Metals of Major Public Health Concern

Any metallic element that is toxic is regarded as a heavy metal (Lenntech, 2004; Duruibe, et al., 2007). Metals and metalloids with atomic density greater than 5 g cm^{-3} and atomic mass that is higher than 40 are considered to be heavy metals (Duruibe, et al., 2007). Furthermore, heavy metals cannot be degraded or destroyed (Timothy and Williams, 2019). Out of all ninety naturally occurring elements fifty three are considered to be heavy metals. Among them, iron, molybdenum and manganese are vital as micronutrients. Zinc, nickel, copper, cobalt and chromium are considered toxic elements which are also vital as trace elements. Silver, arsenic, mercury, cadmium, antimony and lead have no known function as nutrients and are toxic to plants and microorganism. Elements that are persistent in all parts of the environment and of highest concern among the public are tin, thallium, chromium, nickel, mercury, manganese, cadmium, cobalt, copper and lead (Zhang, et al., 2012; Timothy and Williams, 2019). Heavy metals are found in different forms such as phosphates, oxides, silicates, hydroxides, sulphides, sulphates and organic compounds. When they are not metabolised by the body, they accumulate in the soft tissues and as a results they turn out to be toxic to human or animal health (Masindi and Muedi, 2018).

Properties of Heavy Metals

According to Rajeswari and Sailaja, (2014) and Briffa et al., (2020) heavy metals:

- Occur near the bottom of the periodic table.
- Have high densities over 5 g cm^{-3}.
- Are toxic in nature.
- Are persistent.
- Are non-degradable.

Emission of Heavy Metal Contamination on the Environment

From the time of earth's formation, heavy metals originate naturally on the surface of the earth (Briffa, et al, 2020). Furthermore, they become concentrated as a result of human caused activities (Rajeswari and Sailaja, 2014) and finally get deposited in air, soil and water (Masindi and Muedi, 2018).

Natural Emission

Natural sources of heavy metals into the environment are volcanic eruptions, rock weathering, forest fires, biogenic sources, sea-salt sprays and wind-borne soil particles (Herawati, et al., 2000; Masindi and Muedi, 2018). Volcanic activity (such as geothermal activity or magma degassing), continental weathering and forest fires contribute more to the release of heavy metals into the environment (air, soil and water), (Naggar, et al., 2018). Heavy metals such as copper; mercury; lead; arsenic; chromium; cadmium; zinc and nickel are mostly released naturally. Although heavy metals released naturally are found in traces, they have the potential to cause medical problems to human beings and mammals (Herawati, et al., 2000; Masindi and Muedi, 2018).

Anthropogenic Emission

Human activities have significantly increased the global emissions of trace metals in the surface environment (Nriagu, 1979). The release of pollutants to different environmental sections is contributed by activities such as agriculture, mining, industries, wastewater, metallurgical processes and runoffs. Heavy metals are emitted from industrial areas as a result of wind-blown dusts. Automobile exhaust, smelting, the use of insecticides and burning of fossil fuels also contribute significantly to the release of heavy metal such as lead; arsenic; copper; zinc; nickel; vanadium; mercury; selenium and tin in the environment. The need to meet the demands of large population through every day manufacturing of goods, have made human activities to be the most contributor of heavy metal pollution on the environment (He, et al., 2005; Masindi and Muedi, 2018). The rate of most heavy metals emissions into the environment as a result of anthropogenic activities surpass or equate natural emission rate (Naggar, et al., 2018).

Environmental Pollution from Heavy Metals

Environmental pollution by heavy metals has become a global concern due to the increase in usage in different activities to supply the needs of the increasing population (Masindi and Muedi, 2018). When heavy metal occurs in high concentration that leads to a harmful effect to both human and environment it is regarded as a pollutant. Heavy metals such as arsenic; cadmium; chromium; copper; lead; mercury; selenium; nickel; silver and zinc are considered pollutant and harmful whereas metals such as cesium; uranium; strontium; cobalt; manganese; molybdenum and aluminium are considered less common metallic pollutants (Mcintyre, 2003; Timothy and Williams, 2019).

Air Pollution by Heavy Metal

As a result of industrialisation and urbanisation, air pollution has become a serious universal environmental challenge (Masindi and Muedi, 2018). Air polluted with heavy metals is of a societal concern and considered form of pollution which is lethal. Particulate matters into air are released naturally via volcanic eruptions, rock weathering, dust storms and soil erosion whereas anthropogenic activities such as transportation and industrial activities releases large quantities of heavy metals into the atmosphere (Bilos, 2001; Timothy and Williams, 2019). Particulate matters can cause medical problems such as infections of respiratory tracts, cardiovascular infections, skin, eyes irritation and even untimely death. They can also contribute to environmental problems such as eutrophication, acid rain, haze and corrosion of infrastructure (Soleimani, 2018; Herawati, et al., 2000; Masindi and Muedi, 2018).

Soil Pollution by Heavy Metals

Soil pollution by heavy metals is mostly contributed by the release from activities such as industrial; wastewater irrigation; use of fertilisers, manures and insecticides; mine tailings; disposal of waste comprising metals; gasoline and paints with lead; combustion of coal and petrochemicals leakage (Musilova, 2016; Masindi and Muedi, 2018). Globally, soil pollution from heavy metal are of ecological concern due to their nature of being non-degradable and persistent in soil. As a result of their accumulation in soil, they become threat to soil microorganisms and biota (Okunola, et al., 2007; Oke and Vermeulen, 2016; Timothy and Williams, 2019).

The estimation of heavy metals concentration in soil is in the range of approximately less than one to 100,000 mg/kg. Soil functioning systems may be affected by the long term problems on the biogeochemical cycle as a results of soil pollution by heavy metals (Joshua, et al., 2015, Timothy and Williams, 2019). The presence of heavy metals in soil is a serious problem due to its habitation in food chains as it results in destruction of the entire ecosystem (Musilova, 2016; Masindi and Muedi, 2018).

Water Pollution by Heavy Metal

According to Timothy and Williams, (2019) water pollution generally refers to substances that have accumulated in water in an amount that is likely to affect people or animals. At higher amount, all metals are considered toxic and their occurrence in water result to water pollution (Timothy and Williams, 2019). Too much concentration of heavy metals can have detrimental effects to the organisms. The accumulation of plutonium, mercury and lead over time in animal's body can cause serious illness as they are toxic and have no known health benefits on organisms (Lane, et al., 2011; Timothy and Williams, 2019). One of the universal leading root cause of diseases is water pollution. It has been reported to be responsible for the deceases of more than 14,000 persons on a daily basis (Timothy and Williams, 2019).

Industrialisation and urbanisation has been considered as two factors that has intensified level of water contamination by heavy metals. Runoff from urban, municipalities, and industrial areas cause accumulation of heavy metals in soil and water bodies sediments (Musilova, 2016; Masindi and Muedi, 2018). Even in their tiny traces, heavy metals in water can still be very toxic and results in serious health complications to humans and other ecosystems. Food chains and food webs signify the connections between organisms. Water pollution by heavy metals really disturbs all organisms. For example, humans as an organisms that feeds at the highest degree are more prone to health complications as a result of increase of heavy metals in the food chain (Lee, et al., 2002; Masindi and Muedi, 2018).

Potential Exposure Pathways

When heavy metals are not metabolised by the body they accumulate in soft tissues and as a result they turn out to be toxic (Masindi and Muedi, 2018). Health risks from heavy metals exposure are reliant on both dose and rate of exposure (Davies and Mundalamo, 2010). Humans can become exposed to heavy metals in soil, dust or water through several routes such as inhalation, ingestion or skin contact. Exposure pathways to heavy metals permit the targeting of various body tissues or organs such as lungs and the bloodstream system (WHO, 2010; Davis and Mundalamo, 2010; Sepadi, 2019).

- Inhalation: take place as a results of inhalation of particulate matter from mining, agricultural activities, residential or industrial sites.
- Ingestion: comes about through eating of food with high concentrations of heavy metals. Through intentional or unintentional ingestion of earth materials with high level of heavy metals (Davies and Mundalamo, 2010).
- Dermal or skin contact: emerges as a result of contact with minerals, soil or water contaminated by heavy metals (Davies and Mundalamo, 2010).

Toxicity and Health Issues from Heavy Metal Pollution of Major Public Concern

Exposure to some heavy metals has been associated to a huge variety of adverse health effects, including cancer. Moreover, although some elements are essential for humans, they can be dangerous at relatively high exposure levels (Nadal, 2005). Considering their potential toxicological importance, heavy metal pollution of major public concern include: Cadmium; Mercury; Lead; Chromium; Zinc and Arsenic.

Cadmium

Cadmium at very low concentration is toxic. Long term human exposure of cadmium may cause renal dysfunction. Inhalation of dusts and fumes containing cadmium can cause lung illness and cadmium pneumonitis. As a results of lung infections from cadmium exposure, excessive accumulation of watery fluids may develop and cause death of lung tissue, chest pains, cough with foams and mucus with blood. Cadmium may also increase blood pressure, cause bone weaknesses, unprompted fractures, osteomalacia, osteoporosis and myocardic dysfunctions. Effects of cadmium exposure depends on the level of exposure and may result in symptoms such as nausea, vomiting, abdominal cramps, dyspnea and muscular weakness. Furthermore, the end results of severe exposure to cadmium are pulmonary odema effect and mortality. Respiratory and renal problems may occur after sub-chronic inhalation exposure to cadmium and its compounds (Young, 2005; Duruibe et al., 2007).

Mercury

Medical problems linked with mercury exposure are both acute and chronic. Acute exposure my cause excessive salivation, ataxia and abnormal reflexes in children; pharyngitis; dysphagia; abdominal pain; nausea and vomiting; bloody diarrhoea and shock; swelling of the salivary glands; stomatitis; loosening of the teeth; nephritis and hepatitis. Chronic exposure of mercury may results in increased excitability, irritability, psychiatric disturbances, and vibrations. Furthermore, health implications of mercury exposure mostly cause damage to neurological and renal system. However, problems that affect the lungs; kidneys; cardiovascular and immune systems; vision and hearing; that cause paralysis, insomnia and emotional instability may develop as a result of mercury exposure. Unplanned abortion, pregnancy problems in women, acrodynia or pink disease may also happen as a results of mercury exposure (WHO, 2014).

Lead

It is one of the most remarkable poisonous metal among the heavy metals. Exposure to the inorganic forms of lead mostly occurs through food and water ingestion and inhalation of particulate matters. A remarkably severe consequence of lead toxicity is its teratogenic effect. Lead exposure may cause severe and prolonged impairment to nervous system; cause inhibition of the synthesis of haemoglobin; kidney dysfunctions; dysfunction of joints and reproductive systems (Ogwuebgu and Muhanga, 2005). Furthermore, lead may cause impairment to the gastrointestinal tract and urinary tract causing bloody urine; neurological disorder; severe and permanent damage to the brain. In children, lead may cause deprived development of brain grey matter which causes reduced intelligent quotient (IQ), (Udedi, 2003; Duruibe et al., 2007). Psychosis may also occur as results of acute and chronic effects of lead (Lenntech, 2004; Duruibe et al., 2007).

Chromium

Chromium metal and chromium (III) compounds are regarded as non-health hazard (Rajeswari and Sailaja, 2014). Non-carcinogenic effects on the liver, kidney, gastrointestinal and immune systems may occur as a results of chronic exposure to Cr (VI), (Nadal, 2005). Inhalation of high concentration of chromium (VI) can results in irritation to nose lining and even nose ulcers. One of the notable health implications in animals as a results of ingestion of chromium (VI) compounds are stomach irritation; stomach and small intestine ulcers; damage to sperm and reproductive systems particularly in male and anaemia. However, such health implications do not occur due to exposure to chromium (III) compounds as it is much less toxic.

Chromium (VI) or chromium (III) exposure may cause complex reactions and allergies to some persons which may results in severe inflammation and skin swelling. Ingestion of chromium (VI) in drinking water has been reported to cause stomach cancer in both animals and humans. Deliberate or inadvertent ingestion of very high doses of chromium (VI) compounds by human beings may results in severe respiratory, cardiovascular, gastrointestinal, hematological, hepatic, renal and neurological effects or even death (Tchounwou, et al., 2014). The ability of chromium to cause cancer in human and terrestrial mammals is very strong however the manner in which it results in cancer is entirely not understood (Chen, et al., 2009; Tchounwou, et al., 2014). A value of 3×10^{-3} mg/kg/day has been recommended as chromium oral reference dose in the drinking water (Nadal, 2005).

Zinc

Ingestion of zinc is regarded to be quite non-toxic. Zinc is one of an essential element vital for regulating biochemical and physiological functioning of tissues (Tchounwou, et al., 2014). Zinc play a fundamental part in growth regulation, cell production and maintenance of stability. Lack of zinc may cause cells to die (Brieffa, et al., 2020). High concentration intake of zinc by human may cause system dysfunctions that result in growth impairment and weakening of reproduction system (Duruibe, et al., 2007). Furthermore, health problems associated with zinc toxicities are vomiting; diarrhoea; bloody urine; icterus or yellow mucus membrane; liver failure; kidney failure and anaemia (Duruibe, et al., 2007).

Arsenic

Symptoms of arsenic poisonousness depend on the chemical form that an organism is exposed to. Arsenic acts to coagulate protein, forms complexes with coenzymes and inhibits the production of adenosine triphosphate in the course of breathing. It is regarded as cancer-causing in compounds of all its oxidation states and may results in death at high level of exposure. Arsenic toxicity may also cause a condition which is similar to Guillain-Barre syndrome. Guillain-Barre syndrome is an anti-immune disorder that transpires when the body's immune system incorrectly attacks part of the peripheral nervous system which causes nerve swelling thus leading to muscle weakness (Duruibe, et al., 2007).

Heavy Metal Pollution Assessment Methods

Continuous deposition of heavy metals into soil and sediments is highly influenced by the results of industrialisation and economic development. Channels such as composting; metal mining; refining and refinishing by products; rivers; irrigation; runoff; and atmospheric deposition, introduce heavy metals to soil and sediments. The assessment of heavy metals and degree of contamination in soil and sediments needs pre-anthropogenic information of concentration of heavy metals in order to act as the original values (Barbreiri, 2016; Timothy and Williams, 2019). Pollution indices play a crucial role in effective evaluation of soil pollution with heavy metals (Kowalska, et al., 2018). For effective assessment of soil pollution, environmental quality, decision making and spatial planning, different contamination assessment methods or pollution indices have been developed based on their different procedures (Cheng, et al., 2007; Qingjie, et al., 2008).

Pollution indices are a powerful tool for assessing, processing, analysing and conveying raw environmental information to decision makers, managers, technicians and the public (Caeiro, et al., 2005; Qingjie, et al., 2008). They have the ability to monitor soil quality and ensure future sustainability (Ogunkunle and Fatoba 2013; Kelepertzis 2014; Ripin, et al., 2014; Kowalska, et al., 2018). Possible pollution assessment methods commonly used in the literature for the assessment of heavy metal pollution include but not limited to: geo-accumulation index; contamination factor; pollution load index; enrichment factor; ecological risk factor; multi-element contamination; specific pollution index and generic diatom index.

Geo-Accumulation Index (Igeo)

The geo-accumulation index (Igeo) allows to evaluate pollution level of metal contamination (Mu¨ller 1969; Oke and Vermeulen, 2016; Kowalska, et al., 2018; Timothy and Williams, 2019). According to Ma and Singhirunnusorn (2012), the index of geo-accumulation is commonly applied in the contamination assessment by matching the levels of heavy metal found to the crustal average or background levels originally used with bottom sediments. It is computed by the following equation (1):

$$Igeo = \log_2 [Cn/1.5\ Bn] \quad (1)$$

where Cn signifies the measured concentration of the metal of interest and Bn represents the geochemical background value or crustal average. 1.5 is the constant which is presented to reduce the effect of possible variations in the background values which may be attributed to lithological differences in the sediments or soil (Ma and Singhirunnusorn, 2012). Geo-accumulation values are useful in dividing soil into different quality classes or clusters (Mu¨ller, 1969; Ma and Singhirunnusorn, 2012; Nowrouzi and Pourhabbaz 2014; Oke and Vermeulen, 2016; Kowalska, et al., 2018).

Table 1.1. Igeo classifications (Kowalska, et al., 2018)

Igeo value	Class	Soil quality
Igeo ≤ 0	0	Uncontaminated
0< Igeo ≤1	1	Uncontaminated to moderately contaminated
1 < Igeo ≤ 2	2	Moderately contaminated
2< Igeo ≤3	3	Moderately to heavily contaminated
3< Igeo ≤ 4	4	Heavily contaminated
4< Igeo ≤5	5	Heavily to extremely contaminated
Igeo > 5	6	Extremely contaminated

Contamination Factor (CF)

Contamination factor is helpful in the assessment of soil pollution. It permits the evaluation of soil pollution by taking into consideration the content of heavy metal in the soil and pre-industrial reference levels or background values (Kowalska, et al., 2018). The contamination factor (CF) is calculated by the equation (2) below:

$$CF = C\ sample\ /\ C\ background \quad (2)$$

where C sample represents the determined metal concentrations and C background is the metal background concentration. The contamination factor values are categorised into four different clusters, CF < 1 indicates low contamination; 1 ≤ CF < 3 indicates moderate contamination; 3 ≤ CF ≤ 6 describes considerable contamination and CF > 6 describes very high contamination (Mmolawa, 2011; Addo, et al., 2012).

Pollution Load Index (PLI)

Pollution load index is used to assess the degree of soil contamination. It provides a simple procedure to verify how soil conditions has deteriorated due to the increase of heavy metals (Varol 2011; Taofeek and Tolulope, 2012; Kowalska, et al., 2018). The pollution load index (PLI) is computed by the following equation (3):

$$PLI = n \sqrt{} (CF1 \times CF2 \times CF3 \times .... CFn) \quad (3)$$

where n represents the number of metals analysed and CF connotes the contamination factor computed by the equation (2). The pollution load index offers easy but fundamental ways to assess the quality of site as described in Table 1.2 (Kowalska, et al., 2018).

Table 1.2. Pollution load index (PLI) values (Kowalska, et al., 2018)

PLI Value	Category
0 < PLI ≤ 1	Unpolluted
1 < PLI ≤ 2	Moderately to unpolluted
2 < PLI ≤ 3	Moderately polluted
3 < PLI ≤ 4	Moderately to highly polluted
4 < PLI ≤ 5	Highly polluted
5 < PLI	Very highly polluted

Enrichment Factor (EF)

Originally it was established to predict the source of elements in the atmosphere, precipitation, or seawater (Duce, et al., 1975; Qingjie, et al., 2008). It is now commonly used to predict or speculate the origin or sources of pollution in soils, lake sediments, peat, tailings, and other environmental materials (Reimann and de Caritat, 2005; Qingjie, et al., 2008). The formula to calculate EF is:

$$EF = (E/R)\ sample\ /\ (E/R)\ background \quad (4)$$

where E represents the concentration of an element and R denotes a reference element of crustal material. Therefore, E/R sample is the concentration ratio of E to R in the collected samples and E/R background is the concentration ratio of E to R in the earth's crust. According to Ghavanati, et al., (2019), EF values $0.05 \leq EF \leq 1.5$ show that the toxic metal originated completely from crustal materials or a natural source, while values greater than 1.5 would show anthropogenic source of toxic metals. Degree of pollution can be categorised in five classes (Zhang and Liu, 2002; Qingjie, et al., 2008; Sebaiwa, 2016; Ghavanati, et al., 2019).

Table 1.3. Enrichment categories of EF values (Ghavanati, et al., 2019)

EF Value	Category
EF < 2	Depletion to minimal enrichment
EF = 2-5	Moderate enrichment
EF = 5-20	Significant enrichment
EF = 20-40	Very high enrichment
EF > 40	Extremely high enrichment

Ecological Risk Factor (Er^i)

An ecological risk factor (Er^i) to quantitatively express the potential ecological risk of a given contaminant was suggested by (Håkanson, 1980; Qingjie, et al., 2008). Ecological risk factor is useful in the evaluation of the degree of ecological risk triggered by heavy metal concentrations in different environmental compartment such as soil, water, and air, (Kowalska, et al., 2018; Alsafran, 2021). It is calculated by equation (5) below:

$$Er^i = Tr^i \times C^i_f \quad (5)$$

where Tr^i refers to the toxic response factor for a particular element and C^i_f denotes the contamination factor. Ecological risk factor is described by different terminologies: $Er^i < 40$ describes low potential ecological risk; $40 \leq Er^i < 80$ describes moderate potential ecological risk; $80 \leq Er^i < 160$ describes considerable potential ecological risk; $160 \leq Er^i$ describes high potential ecological risk; while $Er^i \geq 320$ describes very high ecological risk (Qingjie, et al., 2008).

Multi-Element Contamination (MEC)

Multi-element contamination index was established by Adamu and Nganje in (2010) to provide a means to measure pollution grounded on the concentration of heavy metals in soil (Kowalska, et al., 2018). Multi-element contamination concentration or values higher than 1.0 indicates heavy metal concentration in soil as a result of an anthropogenic sources. Multi-element contamination concentration <1.0 indicates heavy metal concentration from natural origin. It is computed by equation (6) below:

$$MEC = (C_1 / T_1 + C_2 / T_2 + C_3 / T_3 + ... C_n / T_n) / n \quad (6)$$

where C denotes the content of heavy metal, T represents the tolerable levels and n signifies the number of heavy metals (Adamu and Nganje, 2010; Kowalska, et al., 2018).

Specific Pollution Index (SPI) and Generic Diatom Index (GDI)

Specific pollution index and generic diatom index are two diatoms indices which are commonly used to gather data on nutrients, acidification, eutrophication, organic pollution and general water quality. According to Kelly, et al., (2007), as cited by Matlala (2010), these methods are good in evaluating the concentration of contamination in water. However, they are unable to measure ecological status. SPI and GDI are described as the average mean of the water quality optima (which is the tolerance limits of diatoms to water quality variables) of the texa in the sample, weighted by the quantity of each taxon. They are both grounded on the weighted average mean of the Zelinka-Marvan equation (1961) as presented in equation (7):

$$Index = \sum^{n}_{j}= 1^{ajsjvj} / \sum^{n}_{j} =1^{ajvj} \quad (7)$$

where aj represents the proportion or an abundance of species j in a sample, vj denotes an indicator value and sj signifies a pollution sensitivity of species j. These indices are categorised into five sensitive groups as indicated in Table 1.4 below (Matlala, 2010):

Table 1.4. Evaluation of water quality using specific pollution sensitive index and generic diatom index (Matlala, 2010)

Water Quality Class	State	IPS	GDI
I	Very good	>17	>17
II	Good	15-17	14-17
III	Moderate	12--15	11--14
IV	Poor	12--8	11--8
V	Bad	<8	<8

Health Risk Assessment Method

The health risk assessment model is used to assess the health risks associated with trace elements exposure in the environment (soil, water or air) for both children and adult. Exposure pathways to heavy metals may occur through ingestion, inhalation, and dermal contact (Qadeer, et al., 2020). Non-carcinogenic and carcinogenic risk of trace elements in various environmental compartment through these exposure pathways may be assessed.

Non-Cancer Risk Assessment

To assess the non-cancer health risks, the average daily dose (ADD) of each analysed heavy metals through ingestion, inhalation and dermal contact is calculated (Gabarron, et al., 2017). It is computed by the use of equations (8) – (10) (USEPA, 1996, Gabarron, et al., 2017; Qadeer, et al., 2020).

$$ADD_{ing} = C \text{ x } IngR \text{ x } CF \text{ x } EF \text{ x } ED / BW \text{ x } AT \quad (8)$$

$$ADD_{inh} = C \text{ x } InhR \text{ x } EF \text{ x } ED / BW \text{ x } AT \text{ x } PEF \quad (9)$$

$$ADD_{derm} = C \text{ x } SA \text{ x } CF \text{ x } SL \text{ x } ABS \text{ x } EF \text{ x } ED / BW \text{ x } AT \quad (10)$$

where ADD_{ing} signifies the average daily ingestion (mg/kg/day) exposure amount of an element, ADD_{inh} indicates the average daily inhalation (mg/kg/day) exposure amount of an element, and ADD_{derm} specifies the average daily dermal (mg/kg/day) exposure amount of metal. The values of these factors are presented in Table 1.5. Non-carcinogenic risk is then evaluated from the hazard quotient (HQ) for every trace element. It was computed by dividing the ADD calculated in equations (8), (9), and (10) by a particular reference dose (RfD) as shown in equation (11):

$$HQ = ADD / RfD \tag{11}$$

where ADD less than the RfD signifies no possibility of health effects. HQ>1 suggested possibility of health effects while HQ<1 is a sign of no possibility of health effects (Yalala, 2015). The hazard index (HI) is then calculated by adding the HQ of the three various forms of exposure pathways for a corresponding element (Zgłobicki, et al., 2021). It is computed by the equation (12):

Table 1.5. Exposure factors for dose models (Qadeer, et al., 2020)

Items	Parameter	Meaning	Unit	Value	
				Children	Adult
Basic parameter	C	Concentration of a metal	mg/kg		
	D	Daily dose	mg/kg		
	CF	Conversion factor	kg/mg	1 x 10^{-6}	1 x 10^{-6}
	ED	Exposure duration	years	6	24
	BW	Body weight	Kg	15	55.9
Exposure behavioural parameter	EF	Exposure frequency	days/year	350	350
	AT	Average time (carcinogen)	days	365 × 70	365 × 70
		Average time (non-carcinogen)	days	365 x ED	365 x ED
Digestive tract/inhalation	InhR	Inhalation rate	m^3/kg	5	20
	IngR	Ingestion rate	mg/kg	200	100
	PEF	Particle emission factor	m^3/kg	1.32 x 10^9	1.32 x 10^9
Skin contact	SL	Skin adherence factor	mg/cm^2	1	1
	SA	Skin surface area	cm^2	1800	5000
	ABS	Dermal absorption	-	0.001	0.001

$$HI = (HQ)\ ing + (HQ)\ inh + (HQ)\ derm \quad (12)$$

HI value < 1 describes very low risk, HI value between 1 and 4 shows that the risk effects was possible, and HI value > 4 describes high risk (Zgłobicki, et al., 2021).

Cancer Risk Assessment

The lifetime average daily dose (LADD) of each analysed elements was also calculated for all three potential pathways of exposure (ingestion, inhalation and dermal) using equations (13) – (15), (US EPA, 2002, 1996; Ferreira-Baptista and De Miguel, 2005; Qadeer, et al., 2020).

$$LADD_{ing} = C \times CF \times EF / AT \times (IngR_{child} \times ED_{child} / BW_{child} + IngR_{adult} \times ED_{adult} / BW_{adult}) \quad (13)$$

$$LADD_{inh} = C \times EF / AT \times PEF \times (InR_{child} \times ED_{child} / BW_{child} + InhR_{adult} \times ED_{adult} / BW_{adult}) \quad (14)$$

$$LADD_{derm} = C \times CF \times EF \times SL \times ABS / AT \times (SA_{child} \times ED_{child} / BW_{child} + SA_{adult} \times ED_{adult} / BW_{adult}) \quad (15)$$

where, $LADD_{ing}$ connotes the lifetime average daily ingestion (mg/kg/day) exposure amount of a metal, $LADD_{inh}$ implies the lifetime average daily inhalation (mg/kg/day) exposure amount of an element, and $LADD_{derm}$ indicates the lifetime average daily dermal (mg/kg/day) exposure amount of a metal. Table 1.5 summarised the aspects of exposure for the above models (USEPA, 2002; Ferreira-Baptista and De Miguel, 2005; Li, et al., 2013; Lu, et al., 2014; Gabarron, et al., 2017;Qadeer, et al., 2020). After calculating the LADD of each exposure pathway, a lifetime cancer risk (CR) is then computed by multiplying the LADD with an equivalent slope factor (SL).

$$CR = LADD \times SF \quad (16)$$

The permissible risk usually range from 10^{-6} to 10^{-4} (USEPA, 1991; Rendell and McGinty, 2007; Lu, et al., 2014; Yalala, 2015; Han, 2017).

Conclusion

Heavy metal pollution is problematic globally due to their indestructible and toxic features. In abnormal concentration, heavy metals become toxic to human, animals and plants. Heavy metals occur as a results of both natural and anthropogenic processes. Natural sources of heavy metals are volcanic eruptions, rock weathering, forest fires, biogenic sources, sea-salt sprays and wind-borne soil particles. Anthropogenic sources of heavy metals include coal and fuel combustion; waste disposal; traffic emission; industrial and energy production. Continuous monitoring and assessment of heavy metals pollution levels is vital. The use of pollution indices play a crucial role in the effective monitoring and assessment of heavy metal pollution in the environment. Pollution indices are useful in finding or establishing grounds for correct interpretation of environmental conditions. To properly interpret and comprehend the level and sources of contamination in the environment, the use of proper indices is fundamental.

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Index

G

H

I

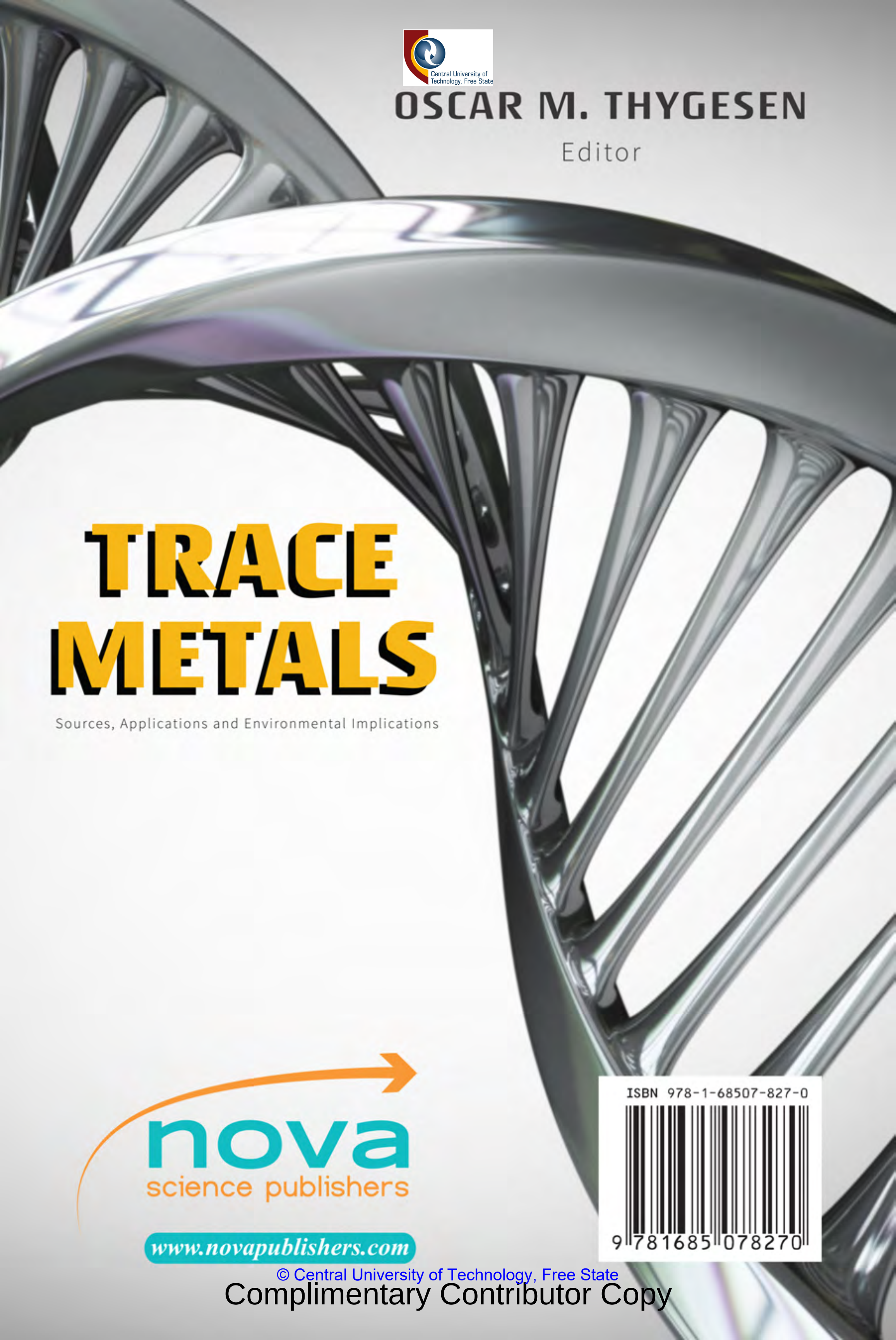
L

M

N

O

P



OSCAR M. THYGESEN

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