ASSESSMENT OF TRACE AND RADIOACTIVE ELEMENTS RISK IN THE ARTISANAL AND SMALL-SCALE GOLD MINING SECTOR

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A Dissertation Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy in Environmental Sciences and Engineering of the Nelson Mandela African Institution of Science and Technology

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ABSTRACT

Currently, the mining industry in Tanzania faces significant challenges including a significant policy research gap. In this work, different indices were applied to assess the health risk of people living and working in Rwamagasa artisanal and small-scale gold mines compared to existing Tanzanian and international standards. This dissertation has focused on quantifying and assessing the risk of selected trace and radioactive elements in a small-scale mining area. Furthermore, the present study analyzed and thus gives some recommendations on issues surrounding the Tanzanian mineral and mining policymaking process. Building on existing work on miner's health risk, the present study asks: What are the levels of trace and radioactive elements in the studied mining areas compared to the recommended local and international limits? What is the health risk due to trace and radioactive elements exposure to mine workers and the surrounding communities? What are some of the deficiencies in the structure of the Tanzanian mineral and mining regulatory framework that are relevant to the environment and public health in artisanal and small-scale gold mines (ASGM)? The hyper pure germanium detector (HPGe) was used for radioactivity analysis. The soil trace elements were analyzed using the energy dispersive X-ray florescence (ED-XRF) technique. The radon gas levels were measured using the Alpha Guard radon monitor. Different literatures survey digest were used to assess the appropriate works on the regulatory and legal framework of the mining sector in Tanzania. The levels of trace elements, carcinogenic and noncarcinogenic health risks revealed that children were more at-risk compared to adults. The hazard index for all pathways was 1.77. This index suggested that the residents of the studied sites were at a high risk of non-carcinogenic effects due to mining operations. The carcinogenic risk for adults and children was found to be 3.42×10^{-5} and 6.16×10^{-5}, respectively, which were higher than the tolerable limit (1×10^{-6}). The results on radioactivity; mean effective dose; annual gonadal equivalent and absorbed dose; radium equivalent; internal and external hazard indices; alpha and gamma indices; and the radon gas revealed high values – approximately 60% higher than the levels that were found in the control area. The Tanzania mining policy-making process needs to have a circular model with the inclusion of scientific inputs as well as societal involvement at every stage of formulation. The present study recommends further studies especially those that use human samples and human subjects in attempting to discover more on the risk posed by mining operations on human health. Also, sustainable mining awareness to people of Rwamagasa is recommended. Furthermore, the present study suggests developing a document that govern the Tanzania artisanal and small-scale mining subsector.

DECLARATION

I, Erasto Focus**,** do hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

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CERTIFICATION

The undersigned certify that have read and hereby recommend for acceptance by the Senate of the Nelson Mandela African Institution of Science and Technology, the dissertation titled "*Assessment of Trace and Radioactive Elements Risk in the Artisanal and Small-scale Gold Mining Sector*" in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy in Environmental Sciences and Engineering of the Nelson Mandela African Institution of Science and Technology.

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DEDICATION

To my late father

Comrade Focus Tindyebwa Ibrahim (R.I.P.)

And my beloved mother

Asteria Matama Kaihura Focus

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LIST OF ABBREVIATIONS AND SYMBOLS

η	Efficiency of a Detector
AAS	Atomic Absorption Spectrometry
ADI	Average Daily Intake
AGED	Annual Gonadal Equivalent Dose
ASGM	Artisanal and Small-Scale Gold Mining
ASM	Artisanal and Small-scale Mining
BoT	Bank of Tanzania
C	Control area (study site, for trace element samples)
COVID-19	Coronavirus Disease-2019
CRM	Certified Reference Materials
CSF	Cancer Slope Factor
CTR	Control Area (Study Site, for Radioactivity Samples)
DCF	Dose Conversion Factor
DIT	Dar es Salaam Institute of Technology
ED	Exposure Duration
EDCI	Effective Dose Coefficient Index
ED-XRF	Energy Dispersive X-ray Florescence
E_{eff}	Effective Dose
E_I	Annual Effective Dose
EIA	Environmental Impact Assessment
EITI	Extractive Industries Transparency Initiative
EPA	Environmental Protection Agency
ESA	Exposed Skin Area
FES	Fraction of Dermal Exposure ratio
FW	Fresh Water
FWHM	Full-Width Half Maximum
GDP	Gross Domestic Product
GPS	Global Positioning System
H_{ex}	External Hazard Index
HI	Hazard Index
H_{in}	Internal Hazard Index

HM	Heavy Metals
HPGe	High-Purity Germanium detector
HQ	Hazard Quotient
IAEA	International Atomic Energy Agency
ICRP	International Commission for Radiation Protection
ILO	International Labor Organization
IMF	International Monetary Fund
IR	Ingestion Rate
I_α	Alpha Index
I_γ	Gamma Index
LSGM	Large-scale Gold Mining
LSM	Large-scale Mining
LVGF	Lake Victoria Goldfields
MD	Mining Pits (Sampling Site for Soil Trace Elements Samples)
MeHg	Methyl Mercury
MEM	Ministry of Energy and Minerals
MJNUAT	Mwalimu Julius K. Nyerere University of Agriculture and Technology
MoEST	Ministry of Education Science and Technology
MP	Mining Pits (Sampling Site for Radioactivity Samples)
NaI	Sodium Iodide
NaI (TI)	Thallium activated Sodium Iodide
N_c	Net Count
NM-AIST	The Nelson Mandela African Institution of Science and Technology
NORMs	Naturally Occurring Radioactive Materials
PEf	Particulate Emission Factor
PML	Primary Mining Licenses
Ra_{eq}	Radium Equivalent Activity
RfD	Reference Dose
SAF	Soil Adherence Factor
SAZ	Standards Association of Zimbabwe
SIA	Social Impact Assessment

TAEC	Tanzania Atomic Energy Commission
TBS	Tanzania Bureau of Standards
UNEP	United Nations Environment Programme
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
URT	The United Republic of Tanzania
USEPA	United States Environmental Protection Agency
W1	Washing Area, A (Sampling Point, for Radioactivity Samples)
W2	Washing Area, B (Sampling Point, for Radioactivity Samples)
WA	Washing Area, A (Sampling Point, for Trace Elements Samples)
WB	Washing Area B (Sampling Point, for Trace Elements Samples)
WL	Working Level
WHO	World Health Organization

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Trace elements are ubiquitously found in nature; nevertheless, human activities might augment their prevalence in the environment. Trace element or heavy metal contamination is a major source of worry around the world (World Health Organization [WHO], 2011). Heavy metals are defined as metals with a specific gravity of less than 5 grams per cubic centimeter (Al-Jubouri & Bashbosh, 2012). These metals or metalloids are well-known for their potential toxicity, particularly from an environmental standpoint (Alloway, 2012). In addition, they are known as trace elements because they can be found in small amounts in a variety of environmental components such as soil, food, water, and air. The prevalence of heavy metals in both terrestrial and aquatic environments is significant in determining possible hazards to human health (Asaduzzaman *et al.,* 2015; Bhuiyan *et al.*, 2015). Some metals are essential to human and other living things at a defined amount, while others are hazardous to living things even in small quantities.

Elements, such as iron (Fe), magnesium (Mg), calcium (Ca), sodium (Na) and potassium (K) are known as microminerals and are essential to our bodies in large amounts for proper metabolism and organ function. Other elements such as copper (Cu), manganese (Mn), lithium (Li), zinc (Zn), chromium (Cr), selenium (Se), germanium (Ge) and cobalt (Co) have been reported to cause non-carcinogenic effects to humans when taken in excess amounts (Li *et al.*, 2013; Santos *et al.*, 2004). Furthermore, metals such as strontium (Sr), silicon (Si), nickel (Ni), silver (Ag), vanadium (V), tin (Sn) and aluminum (Al) may be beneficial microminerals even if their significance in the human body is unknown (Rwiza *et al.*, 2016; Santos *et al.*, 2004).

Metals that are required in trace amounts in human body functions become poisonous and might cause health problems if their recommended health limits are exceeded (Islam *et al.*, 2015; Khan *et al.*, 2014; Siegel, 2002). Toxic heavy metals, on the other hand, are group of minerals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), barium (Ba), antimony (Sb) and bismuth (Bi) that have no known biological function in the human body and are harmful even in small amounts (Asaduzzaman *et al.*, 2015; Focus *et al.*, 2021; Goyer & Clarkson, 1996; Rwiza *et al.*, 2016). Overconsumption, deficiency, or imbalances in the supply of minerals can have serious negative effects on human health (Santos *et al.*, 2004; WHO, 2011). Metal concentrations beyond the tolerable levels can cause dysfunctional cardiovascular, renal, neurological bone disorders, mutagenic effects, and damage to the lungs, kidneys, liver, and other essential organs (Nordberg *et al.*, 2014).

Heavy metals tend to bioaccumulate because they cannot be easily broken down. They survive in the environment and can be moved from one location to another. Humans consume them daily through soil, food, water and air. The type of metal, the dose ingested, and whether the exposure was acute or prolonged all influence human symptoms and toxicity levels (Kamunda, 2017). Some heavy metals cause cancer, while others cause noncarcinogenic effects to the body's organs (Rwiza *et al.*, 2016).

To obtain precious minerals, most mining operations also use harmful chemicals (Sengupta, 2021). Heavy metals such as mercury, which are added to the ore throughout the gold recovery process (especially in the Artisanal and Small-Scale Gold Mining [ASGM]), are examples of such harmful compounds. When the valuable mineral is recovered, the crushed ore and chemicals become waste, which is stacked in enormous slime dams as tailings. In some situations, tailings have resulted in some of the biggest environmental disasters (Lottermoser, 2010; Stéphane & Francis, 2000). When wet tailings break, toxic waters can kill aquatic life and contaminate drinking water supplies for many kilometers down streams (Sengupta, 2021).

Acid mine drainage may be produced during mining activities, which could have a long-term negative impact on underground water, dug wells, ponds, rivers, streams and lakes. When sulphide-bearing minerals, such as pyrites, are exposed to oxygen and water, sulphuric acid is produced (Sengupta, 2021). Heavy metals such as Cd, As and Pb are dissolved by sulphuric acid in rock dumps, mine tailings, and other openings. Due to the massive amounts of exposed rock at some mining sites, the process could take decades (Schmiermund & Drozd, 1997).

Mining operations also pollute the air with particulate matter carried by the wind due to excavations, blasting, and material transportation. Pollutants that enter the atmosphere undergo physical and chemical modifications before reaching a receptor such as human beings. These contaminants, particularly trace and radioactive elements, have the potential to harm people's health (Sengupta, 2021). The ASGM areas have been frequently reported to have higher levels of trace and radioactive elements (Mwaipopo *et al.*, 2004). In this work, the term "artisanal" refers to disorganized mining that does not employ sophisticated machinery, whereas "small-scale" refers to organized miners who do not necessarily use advanced machinery but have a greater revenue turnover than the artisanal.

Natural radionuclides produced from primordial and cosmogenic sources are found in varying concentrations in our environment. This is due to the material that the earth was formed from approximately 4.5 billion years ago (Pentreath, 2021). The Earth contains several unstable nuclides that continue to expose humans to radiation as they disintegrate. Some levels of natural radioactivity are normal but even when normal, radioactivity may differ significantly in different locations (Abbasi & Mirekhtiary, 2020). These differences have been associated with different anthropogenic activities, such as gold mining, which is usually responsible for a high volume of mine wastes (McKinnon, 2002). High amounts of natural radionuclides from these activities are released into the soil, air and water, leaving a legacy of environmental contamination in residents and working places (Kamunda, 2017). Natural radiation in the environment is generally at levels that are not hazardous to human health (Frumkin, 2001). However, the increased radiation concentrations are a source of worry for radiation protection and have recently been a worldwide topic of investigation (International Atomic Energy Agency [IAEA], 2005; International Commission for Radiation Protection [ICRP], 2019; United Nations Scientific Committee on the Effects of Atomic Radiation [UNSCEAR], 1993, 2020). Naturally occurring radioactive materials (NORMs) are words ascribed to these radiations. The NORMs are responsible for up to 85% of the world's population's annual dosage exposure (Sarkar, 2019).

The NORMs are classified into three groups, namely cosmogenic, terrestrial and anthropogenic based on the source of origin. The interaction of cosmic rays with the earth's atmosphere produces cosmogenic radionuclides (Sarkar, 2019). Radionuclides such as ^{14}C, ^{7}Be, ^{22}Na and ^{3}H are formed when they interact with stable nuclides in our environment (Tykva & Berg, 2004). Terrestrial radionuclides also called primordial radionuclides (Faanu *et al.*, 2011; UNSCEAR, 2000) come from the earth's bedrock, food stuffs and beverages. The anthropogenic source is mainly due to human activities such as mining and mineral processing (ICRP, 2019).

Uranium, thorium and their progeny are the most common natural radionuclides and contribute the most to human radiation exposure (UNSCEAR, 2020). Uranium (^{238}U), with a half-life of 4.5 billion years, ^{235}U, having a half-life of 700 million years, and ^{232}Th, with a half-life of 14.1 billion years, are the three primary decay series found in nature. The nuclides in each of the decay chains headed by ^{238}U, ^{235}U, and ^{232}Th decay by alpha or beta particles followed by gamma radiation until they reach the most stable ^{206}Pb, ^{207}Pb, and ^{208}Pb nuclides, respectively (Al-Sulaiti, 2011).

The earth's crust contains about 2.7 mg/kg of uranium (Santos-Francés *et al.*, 2018). In a natural environment, uranium and radium are frequently more soluble than thorium. Uranium includes 99.28% ^{238}U, 0.72% ^{235}U, and trace levels of roughly 0.0058% ^{234}U in the natural environment (Faanu *et al.*, 2011). The high abundance of ^{238}U makes it common in many radiations protection studies. The ^{238}U goes through fourteen radioactive decay steps in its decay chain, releasing eight alpha-particles with a maximum energy of 7.687 MeV and six beta-particles with a maximum energy of 1762.6 keV (Faanu *et al.*, 2011). Gamma rays with energies ranging from 46.53 to 2447.86 keV are also released throughout the decay scheme. The decay chain segment beginning with radium (^{226}Ra) is radiologically the most important in the ^{238}U series because it behaves chemically similar to calcium (Asaduzzaman, 2017) and is accumulated on bone surfaces and areas of mineral metabolism. As a result, ^{226}Ra is often used instead of ^{238}U.

The principal sources of thorium are monazite, and thorium phosphate rocks. The solubility of thorium in natural waterways is significantly poor, and it is essentially transported in a particulate form. Clay minerals have it adsorbed on their surfaces. Thorium (^{232}Th) undergoes 11 radioactive decay stages over its lifetime, producing mainly seven alpha particles with a maximum energy of 8.784 MeV and five beta particles with a maximum energy of 834.2 keV (Xiong *et al.*, 2019). Gamma rays with energy ranging from 13.51 to 2614.533 keV are also released during the ^{232}Th decay chain. Because the ^{232}Th isotope decays to generate ^{228}Ra, which is similar to ^{226}Ra and radiologically significant, ^{228}Ra is sometimes used instead of ^{232}Th.

Radium-226 (^{226}Ra), with a half-life of 1600 years, decays to give an alpha particle and Radon-222 gas (^{222}Rn). Radon-222 with a half-life of 3.82 days is a very dangerous gas which also disintegrate to produce alpha particles to its daughters (Polonium-218 and Polonium-214) (Gillmore *et al.*, 2001; Tung, 2001). During the decay process, before reaching a stable ^{206}Pb, significant numbers of alpha and beta particles are released. Radon gas becomes dangerous in areas with poor air circulation, such as poorly ventilated houses and enclosures such as the mining pits that are of significant interest for radiation protection and control (Gillmore *et al.*, 2001).

Potassium is found in all environmental components, including soil, water, foodstuffs and living organisms, including the human body, and is generally dispersed in the earth's crust (Asaduzzaman *et al.*, 2015). The ^{40}K is the potassium isotope that is the most abundant naturally occurring radioactive isotope (Asaduzzaman *et al.*, 2015; Rahman & Faheem, 2008). The radioactive isotope of terrestrial relevance ^{40}K has an isotopic abundance of 0.0118% and a specific activity of 31.4 Bq/kg (Bakım & Görgün, 2015). The 88.8% majority of naturally occurring ^{40}K decays to stable ^{40}Ca, while the remaining 11.2% decays to stable ^{40}Ar via electron capture and positron emission (James *et al.*, 2013). During the decay process, ^{40}K undergoes 100 disintegrations, of which 89 produce alpha particles with a maximum energy of 1.33 MeV and 11 produce distinctive gamma photons with a maximum energy of 1.46 MeV (James *et al.*, 2013).

Long-lived natural radionuclides of uranium (U), potassium (K), and the thorium decay family have been shown to be elevated in mining areas (IAEA, 2005). Once in the ecosystem, these radionuclides may also accumulate in soil, water and plants and are eventually consumed by people in high proportions (Kaewtubtim *et al.*, 2017). Radionuclides may enter the human body through ingestion, dermal contact or inhalation and are absorbed by body organs. Cancer and noncancer disorders such as eye lens deterioration, neurological illnesses, diabetes and a variety of other radiogenic illnesses may occur as a result of the health impacts due to radionuclides (Stewart *et al.*, 2012).

For any country's mining industry to be successful in terms of environmental and public health, it must have sound and robust policy, laws, and regulations governing the sector (Maliganya & Bengesi, 2018). These policies, laws and legislation assist in bridging the gap between the environmental-benign, human activities and human rights requirements. The mining industry, for example, may violate human rights associated with clean and healthy environments by deteriorating the environment and community around the mines. Basic livelihood requirements, such as shelter, food and air, are derived from the environment; as a result, environmental pollution makes it difficult to meet these needs (Walwa, 2016). Poor mining policies, laws and regulations can also contribute to poor environmental impact assessments (EIA) and social impact assessments (SIA), resulting in the failure of the project to adhere to human rights.

1.2 Statement of the Problem

According to the World Health Organization (WHO), environmental variables are directly connected to up to 24% of worldwide disease burden (WHO, 2011) via inhalation, ingestion, and body contact pathways. However, some of the repercussions of exposure are difficult to detect, since they appear later in life (UNSCEAR, 2020; WHO, 2002, 2011). It is estimated that, in 2014, 9100 male and 10800 female deaths (mostly cancer cases) occurred in Tanzania due to diseases associated with environmental factors (Olson *et al.*, 2020). In addition, Walwa (2016) reported the deaths of 63 people, 1000 cattle, 523 goats, 185 sheep and 227 dogs in the villages surrounding the Barrick North Mara Gold Mine (NMGM) due to mine pollution. According to the literature, there is a link between mining pollution, mortality rate, and number of cancer cases (Knoll, 2000; Knoll, 2010; UNSCEAR, 2020).

Based on the field observations in the area where the present study was conducted, with the evidently poor working environment (Fig. 1), recent investigations on environmental pollution and human health risk from Tanzania small-scale gold mines are deficient in three ways. First, studies related to exposure to radionuclide emissions are rare and sparse. Second, most of the data presented on the effects of trace elements for ASGM are not exhaustive, lacking other elements than mercury and cyanide. Third, the Tanzanian mining and mineral policies, laws and regulations for handling environmental and public health issues due to mining activities require intensive reviews (Lissu & Mark, 2008; Walwa, 2016). Therefore, this work assessed the risks, correlations, and hazard indices due to mining pollution at one of the small-scale gold mines combined with an analysis of the mining and mineral policy-making process in Tanzania.

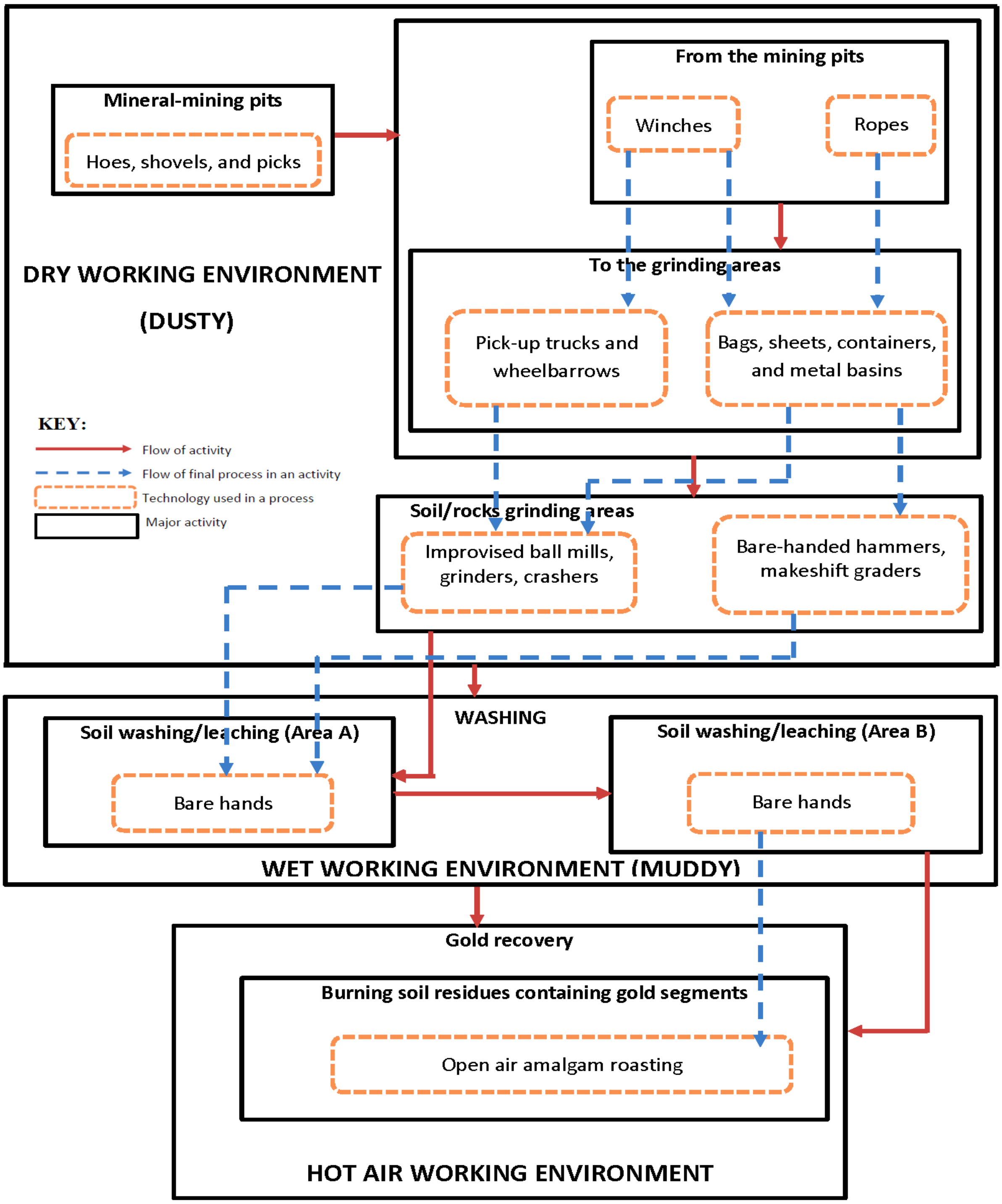


Figure 1: **Interpretation of the working environment at Rwamagasa ASGM based on field observations**

1.3 Rationale of the Study

This research investigated the pathways through which miners are exposed to trace and radioactive elements from different sources. The present study provides information on the state of environmental contamination in the study area and uses pollution indices to evaluate the risk of exposure for miners and other people who live and work in the mining sector. The present study also gives site-specific data on radioactive and trace elements to promote gold mining best practices at not only for the study area but also for other mining locations in Tanzania. Furthermore, the present study examines Tanzania's mineral and mining policymaking to contribute to long-term mining operations. Thus, the findings of the present study can be used as a starting point for developing national guidelines for the concentrations and doses of radioactive and trace elements in the mining industry. The findings are also a potential aid to policy makers and all mining stakeholders in improving the mining environment in Tanzania.

1.4 Research Objectives

1.4.1 General Objective

The study aimed at assessing trace and radioactive elements risk in the artisanal and small-scale gold mining sector of Tanzania.

1.4.2 Specific Objectives

The following were the specific objectives that guided the present study:

(i) To evaluate human health risk of trace elements due to mining activities for people living and working in a mining environment.

(ii) To determine the risk of radioactivity exposure to ASG-miners and mining area dwellers.

(iii) To examine the Tanzanian mining, minerals, and environmental regulatory frameworks with a focus on the ASGM subsector.

1.5 Research Questions

(i) How do ASGM activities put miners and surrounding communities at a health risk due to trace element levels?

(ii) How are miners and people dwelling in mining areas at risk due to radioactivity and environmental radon exposure?

(iii) To what extent do the Tanzania's mining, minerals, and environmental regulatory frameworks address the public health challenges inherent in the ASM/ASGM subsector?

1.6 Significance of the Study

The results of this study have a significant contribution to understanding site-specific needs of the ASGM sector and the implications for ASGM policy making in Tanzania. Findings and recommendations in this study can also be used by ASM/ASGM stakeholders in planning and policymaking, to a more sustainable ASM/ASGM sector. Raw data and associated analysis results have been published in international journals with Open Access option. These can be freely accessed by those who would like to use the findings to promote public health awareness and sustainable policymaking of the ASGM industry. Furthermore, supplementary materials will be left at NM-AIST for further referencing. Furthermore, the main author is a lecturer at MJNUAT, to which these findings will contribute to research and academic advancement purposes.

1.7 Delineation of the Study

The present study aimed at developing an understanding and awareness of the health risks due to radioactive and trace elements in the ASGM sector of the broader extraction industry. The concentrations, hazard indices, the effects of radon gas, and the mineral and mining environment in supporting the ASGM in Tanzania are hereby discussed in detail. This dissertation is divided into five chapters; Chapter One discusses background information on the problem, statement of the research problem, rationale of the study, objectives, research questions, significance, and delineation of the study. Chapter Two presents literature review in which crucial issues influencing levels, health effects of radioactive and trace elements, levels, and risk of radon gas in the ASGM are discussed. Also, the influence of the mining policy environment and laws in protecting health of the environment and miners in the ASGM is discussed. Chapter Three covers techniques and methods used to analyze concentrations, carcinogenic and non-carcinogenic effects, hazard indices and policymaking environment. Chapter Four presents the results and discussion of trace and radioactive elements in the ASGM and analysis of the mining policy and regulatory frameworks. Chapter Five presents the conclusions, scientific and knowledge contributions, and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Tanzania Mining Industry: Overview

The mining industry is known to play a key role in a country's economic development. Economic contributions are typically made through the employment of trained and non-skilled employees, as well as foreign revenue earnings that are required for national economic development (Steven & Edmore, 2010). Mining operations, on the other hand, are known to have negative consequences both on the environment and on human health (Abdel-Shafy & Mansour, 2016; Mutagwaba *et al.*, 2018; Mwaipopo *et al.*, 2004; Walwa, 2016). Small, medium, and large-scale mining operations are often classified based on technology, labor, and capital investment requirements. Small-scale mining activities have been repeatedly reported to have very serious environmental and public health negative consequences. A body of literature (Bose-O'Reilly *et al.*, 2009; Ikingura & Akagi, 1999; Ikingura *et al.*, 2006; Mutagwaba *et al.*, 2018; Mwaipopo *et al.*, 2004; Straaten, 2000) has reported the consequences of trace elements of Tanzania ASGMs. In developing countries such as Tanzania, these consequences have also been linked to poor and insufficient policies, laws, and regulations governing the mining industry (Lissu & Mark, 2008; Maliganya & Bengesi, 2018; Maliganya & Renatus, 2017; Walwa, 2016). To do this, the mining industry should place a strong emphasis on environmental sustainability and human health management (Mutagwaba *et al.*, 2018; Mwaipopo *et al.*, 2004).

Tanzania has been mining gold over several past years (Jolanta *et al.*, 2012), with both Large Scale Gold Mining (LSGM) and ASGM. Over the last few decades, Tanzania's ASGM sector has become increasingly important in reducing poverty across the country. Tanzania's mostly unregulated ASGM industry began to grow in the 1980s. The rise in the number of people working in ASGM in the 1980s and 1990s has been linked to a reduction in other industries, an insufficient market for agricultural products, droughts, and a variety of other livelihood factors (United Nations Environment Programme [UNEP], 2012). According to Jønsson and Fold (2009) the closure of national-owned mines in the 1980s and those held by individuals and the private sector in the early 1960s resulted in semi-skilled individuals engaging in ASGM. However, many ASGM operations carried out throughout the country play a significant role as a direct source of employment, adding jobs and income to the rural economy and contributing to national revenue (Mwaipopo *et al.*, 2004).

Specific statistics for ASGM miners in Tanzania are unclear (Mutagwaba *et al.*, 2018; Mwaipopo *et al.*, 2004). This is due to the lack of a common repository for ASM/ASGM data, information, and research, making it impossible to track ASM/ASGM numbers over time. According to the Ministry of Energy and Minerals (MEM) baseline survey, the number of artisanal and small-scale miners has steadily increased from 150 000 in 1987 to 550 000 in 1996 and 680 385 in 2011 nationally wise, with women accounting for 27.6% (MEM, 2016; Mutagwaba *et al.*, 2018). More recent estimates show that the number of participants is growing. For example, the Minister for Energy and Minerals in his speech to the Tanzanian parliament estimated direct employment in ASM/ASGM activities in Tanzania to be more than one million people (MEM, 2016). Another study on the interaction of ASM / ASGM and agriculture indicated that there are approximately 1.5 million active players of ASM / ASGM in Tanzania, with 9 million people relying on the subsector for their living (Mutagwaba *et al.*, 2018).

The level of investment is also used to classify large, medium, and small-scale mining. The Tanzania Mining Act of 2010 defines a small-scale mine as one with a capital investment of less than $100 000 or its equivalent in Tanzanian shillings (Mutagwaba *et al.*, 2018; URT, 2010). It was reported by Mutagwaba *et al.* (2018) that the ASM/ASGM produces around 4 tons of gold annually accounting for approximately 10 per cent of Tanzania gold production. If the population ratio is directly related to production figures, it can be estimated that the annual ASM/ASGM gold production is around 3.3 tons. However, information on the share of ASM/ASGM to the mining sector Gross Domestic Product (GDP) is lacking. Although it is known that legitimate ASM/ASGM pay 3% of their revenues as loyalty to the government, hence contributing to the national GDP (Mwaipopo *et al.*, 2004).

The Tanzanian government has recently begun the process of formalizing the ASGM. As a result, multiple ASGM entities have emerged around the country, particularly in the Lake Victoria goldfields (LVGF), which has also been linked to environmental deterioration, including increase in radioactive and trace elements.

2.2 Mineral Mining and Trace/Radioactive Elements

Mining operations have been linked to an increase in trace and radioactive elements that were previously at natural background levels (Asaduzzaman *et al.*, 2015; UNCEAR, 1982). This increase becomes critical to environmental and human health, especially to the ASGM sub-sector. This might be due to the lack of knowledge and awareness on trace and radioactive elements, poor mining methods and tools used, insufficient capital, unsupportive policies, laws and regulations and lack of education on proper handling of mining wastes.

For example, a study by Ikingura *et al.* (2006) on Hg pollution and dispersion in environmental matrices in the Rwamagasa and Mugusu ASGMs revealed Hg levels ranged from 0.5 to 6.0 mg/kg in contaminated river sediments near the Mugusu ASGM. Mine tailings from Rwamagasa had the highest concentrations of Hg pollution (165–232 mg/kg). These findings are supported by Bose-O'Reilly *et al.* (2009) who conducted a medical, neurological, and neuropsychological study on 180 samples from the Rwamagasa ASGM. The amount of Hg in people working and living within and around the study area were determined using urine, blood, and hair samples. The Hg concentrations in the biomonitor blood, urine, and hair were statistically substantially higher in the exposed Rwamagasa ASGM population than in the Katoro control group (about 20 km from Rwamagasa). The most exposed demographic group, amalgam-burners, was evaluated. An analysis of Hg in hair revealed that the elevated body levels of artisanal miners were mostly due to elemental Hg vapor. The study by Ikingura *et al.* (2006) misses some other important heavy metals, which could adversely negatively affect human health. It also seems important to include radioactive elements and radon gas that are frequently reported elsewhere to have carcinogenic and noncarcinogenic consequences to humans (Esiole *et al.*, 2019; Madzunya *et al.*, 2020; Ntihabose, 2010; UNSCEAR, 2020).

2.3 Trace Elements and Human Health

Essentially, all living organisms require varying amounts of certain elements to perform certain functions as sources of minerals and vitamins in the body's functioning, but these elements can become poisonous at higher concentrations (Rwiza *et al.*, 2016). Some elements, such as Hg, Pb, Cd and As are known to be harmful even in low quantities while they do not have a recognized positive function in the human body (WHO, 2011). Trace elements accumulate in key organs such as the liver, lungs, kidneys, brain and bones for years after being absorbed by the body, creating serious health concerns. As a result, the US Agency for Toxic Substances and Diseases Registry lists As, Pb and Hg as three serious health and environmental concerns (Ogola *et al.*, 2002).

Water supply and building materials such as soils may be contaminated by trace elements from mining operations. Excessive trace elements accumulation in agricultural soils may cause soil contamination as well as increased trace elements uptake by crops (Muchuweti *et al.*, 2006).

Trace elements are also unintentionally consumed through food, soil and drinks. When consumed, they are found in a variety of tissues and organs after being absorbed. Even if elimination happens through the digestive tract and the kidneys, significant amounts can remain in some storage locations such as the liver, bones and kidneys for years or decades creating a long term health problems (Kabata-Pendias, 1993; WHO, 2011).

2.3.1 Trace Elements Toxicity

(i) Arsenic (As)

Arsenic (As) is believed to be a human carcinogen at extremely low exposure levels (Ng *et al.*, 2003). It is mainly circulated in the skin, kidneys, lungs, liver, spleen, and aorta after absorption. Acute As poisoning can produce throat burning, nausea, diarrhea, stomach pain, vomiting and muscle cramps (Kabata-Pendias, 1993). Chronic exposure to low concentration of As causes peripheral nerve damage seen as tingling, numbness and weakness in the hands and feet, skin hyperpigmentation, as well as diabetes (Kabata-Pendias, 1993; WHO, 2011).

(ii) Lead (Pb)

The Pb is a human mutagen and a probable carcinogen that is recognized to be hazardous even in low quantities (Tchounwou *et al.*, 2012). In adults, it causes kidney tumors, slows cognitive development and raises blood pressure. The Pb toxicity also reduces hemoglobin production, disrupting normal renal, joint, reproductive, and cardiovascular functions, as well as causing persistent damage to the central and peripheral neurological systems (Tchounwou *et al.*, 2012). The neurotoxic effects of Pb appear to be particularly dangerous to children and developing fetuses. According to epidemiological research, Pb poisoning in children under the age of five at low levels has also been associated with deficiencies in intellectual development (Kabata-Pendias, 1993; WHO, 2011).

(iii) Mercury (Hg)

There are two types of Hg, namely, inorganic, and organic Hg. Acute intake of inorganic Hg can result in gastrointestinal problems such as discomfort, diarrhea, vomiting, and bleeding (Graeme & Pollack , 1998). The central nervous system, along with the kidneys, gastrointestinal tract, skin and the liver are severely affected by prolonged and repeated Hg exposure. In the long run, it can cause fatigue, dizziness, headaches, limb discomfort, mood swings, hearing and memory loss, peripheral vision loss, muscular weakness, numbness and tingling and rashes (Tchounwou *et al.*, 2012). The Cd is also harmful at low quantities and is thought to be a likely carcinogen agent. The Cd poisoning can also cause respiratory disorders such alveolitis, bronchiolitis and emphysema (Kabata-Pendias, 1993). The Cd can also cause kidney and reproductive problems. Renal damage can also occur as a result of Cd inhalation over time (Tchounwou *et al.*, 2012). Ingestion of Cd-contaminated food, water, or soil can lead to bone fractures, kidney failure, high blood pressure and possibly cancer (Kamunda, 2017). Some of the strange long-term symptoms include arthritis, anemia, cardiovascular disease, diabetes, cirrhosis, altered fertility, migraines and strokes.

(iv) Chromium (Cr)

Compounds containing chromium (Cr (VI)) are poisonous and are known to be carcinogenic and mutagenic. Despite the fact that Cr (III) is a necessary component in human bodies (Focus *et al.*, 2021) inhaling it at high levels might irritate the nose lining leading to breathing disorders. Prolonged exposure to Cr can harm the liver, kidneys, circulatory system, nerves and cause skin irritation. Not only Cr but also, high levels of Ni has been linked to cancers of the mouth and intestine, depression, heart attacks, haemorrhages and kidney problems (Tchounwou *et al.*, 2012). Excessive use of Zn and Cu, despite their importance to human health, may have non-carcinogenic effects (WHO, 2011). In addition, excessive Cu has been associated with liver damage, whereas in excess, Zn has negative nutritional effects. Increased Zn concentrations can slow growth and reproduction in humans (Hilal *et al.*, 2016).

2.3.2 Trace Elements with Gender and Age Groups

Trace elements constitute a serious threat not only to adults, but also to children in schools, daycare centers, kindergartens, sports facilities and playgrounds, particularly by ingestion (Różański *et al.*, 2021). Różański *et al.* (2021) used the gastrointestinal Unified Bioaccessibility Method (UBM) procedure to assess the human health risk of As, Cd, Pb, Cr, Ni, Cu and Zn related to polluted dust and soils. Różański *et al.* (2021) found that polluted soils posed a noncancer and carcinogenic risk to young people with soil pica behavior, or geophagia difficulties. Children who live near active or abandoned mine sites are more vulnerable to heavy metal effects, both non-carcinogenic and carcinogenic than adults (Kusin *et al.*, 2018).

People can ingest soil material either involuntarily or intentionally, the latter practice being known as geophagia (Peter, 2012). The research conducted by Peter (2012) in the United Kingdom argued on the substantial quantities of soil that can be repeatedly ingested by people, also discussed the consumption of harmful elements to soil consumers. Geophagia is a multi-causal behavior, the 'nutritional hypothesis' in which the deliberate ingestion of soil is attributed to an attempt to manage a mineral nutrient imbalance such as salt shortage. Chemical components can be solubilized and made potentially available for absorption when soils meet digestive fluids, occasionally to the point where poisoning symptoms appear. In areas where deficiencies in certain minerals, such as Fe, stale soil materials are frequently recognized as the primary source of deficient mineral nutrients. The swallowed soil materials have further set of issues, including exposure to potentially harmful radioactive and trace elements, germs, helminths and eggs, fungi in the soil, depending on the geographical area (Nii *et al.*, 2020).

Workers, especially expectant and nursing mothers in ASGMs, would be at high risk of exposure to hazardous substances through accidental and deliberate intake of soil materials. A study by Hunter-Adams (2016) found that in some sub-Saharan African countries, expectant mothers and other women tended to eat non-food materials, a condition known as geophagia (Hunter-Adams, 2016). This introduces a high risk to such groups of communities.

Although not restricted to Tanzania, geophagia, especially for pregnant women, has been extensively studied in sub-Saharan Africa (Abrahams, 1997; Getachew *et al.*, 2021; Kariuki *et al.*, 2016; Kibr, 2021). The condition has also been associated with the risk of exposure to malignant environmental pollutants. In Tanzania, for example, studies have shown that in most cases women eat soil materials famously known as *kipemba* (Nyanza *et al.*, 2014; Yanai *et al.*, 2009). As a matter of fact, the mining of *kipemba* in Tanzania constitutes an ASGM activity. There is a reliable market for these soil materials across the country despite the inherent health implications. The concern is not only these '*official*' soil materials, women, especially those living in the remote rural areas of Tanzania, are known to eat clay-based soils. This is a critical concern, especially for women and girls who live and work in the ASGM sector.

2.3.3 Trace Elements in the Large-scale Mining Sector

Steven and Edmore (2010) investigated the environmental effects of gold mine effluent disposal in Zimbabwe, with a focus on the Tiger Reef gold mine in Kwekwe district. Questionnaire surveys and interviews with key informants were used to gather information on the effects of mining on human health. Field tests and observations were also carried out on parameters such as cyanide and Hg concentrations, which were compared to the WHO and the Standards Association of Zimbabwe (SAZ). According to the Steven and Edmore (2010) findings, waste management techniques at the Tiger Reef Mine were linked to detrimental environmental and human health consequences. The study further reported the lack of monitoring and enforcement of relevant policies, laws, and environmental management regulations by authorities in Zimbabwe. However, Steven and Edmore (2010) did not suggest measures to be taken to make these laws and policies practicable.

To examine the aspects of heavy metal contamination and health concerns, Tang *et al.* (2017) collected street dust from Huainan, a typical coal mining city in China. The findings revealed that Co, Cr, Cu As and Pb levels were generally low to moderate, while Cd and Hg pollution levels were moderate to high. The Cd and Hg concentrations were associated with significant health concerns in 64.3% and 58.6% of the sites, respectively. One-fifth of the samples exhibited substantial hazards linked to Hg contamination. The dust on the streets of the mining area revealed less metal pollution than in other metropolitan areas. Higher metal concentrations in Huainan dust were obtained primarily from activities related to vehicles, industrial emissions, and coal dust weathering. Even though the health risk from individual metals in dusts were modest, the non-carcinogenic risk from multiple metals to children were above the allowed level of 1, implying that the overall risk from multiple metals in dust was alarming.

2.3.4 Trace Elements in the Artisanal and Small-scale Mining / Artisanal and Small-Scale Gold Mining Sector

Small-scale gold mining, sometimes known as "Galamsey" in Ghana, was reported to contribute significantly to trace elements exposure (Kpan *et al.*, 2014). Kpan *et al.* (2014) aimed to establish the extent of heavy metal contamination in the environment because of small-scale miners' activities. The quantities of several selected heavy metals: Hg, Pb and Cu were investigated and detected at 14 sampling sites in Dunkwa-on-Offin, a town known for mining activities in Ghana's central region. Trace element concentrations in water and soil samples from the selected municipalities were analyzed using the Atomic Absorption Spectrometry (AAS) method and compared to the Environmental Protection Agency's (EPA) relevant criteria. The concentrations of the tested heavy metals were significantly higher than those allowed by the guidelines in most areas (WHO, 2011). The Pb concentrations in the soil were reported to be 95.13 mg/kg and 190.27 mg/L in water, while the Cu concentrations were 63.26 mg/kg in the soil and 75.92 mg/L in the water and for Hg, the concentrations were 140.87 µg/kg in the soil and 211.31 mg/L in the water. In the vulnerable zones, the mean reported amounts were significantly higher. The authors concluded that heavy metal contamination in the ASM had become uncontrollable. The authors did not explain the possible reasons that made heavy metal contamination in the ASM persistent, nor did they give an idea of how the government and stakeholders could combat the problem.

In China, Xiao *et al.* (2017) reported soil contamination and health risk in Chinese areas with a history of ASM, the quantities of heavy metals in soils, tailings, cereal and vegetable crops were studied, and the health risk was calculated. The findings revealed that the leftover tailings and prior mining activity had heavily polluted the soils with heavy metals. The primary contaminants in soils were Hg and Cd. Furthermore, Hg and Pb levels in grains and several vegetables were above tolerable levels. Additionally, heavy metal concentrations in wheat grains were higher than in maize grains, and metal concentrations in leafy vegetables were high. The main sources of consumption of Hg, Cd and Pb were local grains. Residents in the area faced substantial chronic hazards from exposure to Hg and Pb, while their carcinogenic risk from Cd inhalation was minimal.

2.3.5 Trace Element Levels in the Tanzania Mining Industry

In Tanzania, different studies have been carried out on the environmental, health, financial, and social issues of the mining sector. While there has been more research on the LSGMs, few researchers have taken into consideration the ASGM subsector. Also, many studies have focused more on the effects of Hg in the ASGM; few researchers have taken into consideration the other trace elements and their effects to human health. Based on the persistence of environmental and public health problems in the ASGM subsector in Tanzania, research has not taken into account the influence of the regulatory environment on controlling mining-related problems and the need to integrate scientific findings into the policy formulation cycle.

Ikingura *et al.* (2006) conducted a study on the southern side of Lake Victoria at Nungwe Bay, reporting Hg concentrations in fish representing various feeding patterns. The findings suggested that the use of Hg in gold extraction in the LVGF resulted in elevated Hg levels. Parmelia lichen was found to be an efficient bioindicator of air Hg contamination as a result of Hg emissions from gold-amalgam fire and purification processes. The Hg levels around the

Mugusu mine were also reported, with the highest concentrations detected near gold-amalgam processing facilities. The researchers, however, made no attempt to estimate the radiological health indices due to ingestion of Hg through fish consumption. Methyl mercury (MeHg) levels in the mine tailings were unexpectedly high (629–710 ng/g), indicating that the oxidation and methylation of metallic Hg in the tailings occurred at high levels. When the tailings were re-equilibrated with freshwater (FW), it was discovered that MeHg was tightly bound to the tailings and that very little MeHg was released into the water column (0.2–1.5 ng/L). When the tropical loamy clay soil contaminated with $HgCl_2$ (5 mgHg/ kg) was inundated with seawater and FW, MeHg values of 11 and 14 ng/g were obtained, respectively. Only a small amount of MeHg (0.4 ng/L) was transported from the soil to the equilibrated water. The first week of atmospheric exposure of soil pre-inundated with FW resulted in net MeHg degradation, followed by net MeHg generation and buildup in the soil up to 15.5 ng/g during atmospheric desiccation. These and other findings provide important information about Hg transformation, mobility, and bioavailability in tropical aquatic systems exposed to Hg pollution from gold mining operations, but they do not reveal the extent to which the residents are affected by Hg.

Furthermore, Rwiza *et al.* (2016) reported groundwater quality in the North Mara mining area in northern Tanzania, elucidating the impact of large-scale mining operations on groundwater quality. Groundwater samples were analyzed for trace element concentrations involving 11 trace elements (Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn). The average values of Fe and Al were higher than those of the Tanzanian drinking water guidelines. The Pb levels in three samples were greater than the 10 and 15 g/L drinking water standards set by the WHO and the United States Environmental Protection Agency (USEPA), respectively. One sample had an As concentration higher than the WHO and USEPA guideline of 10 g/L. The elemental concentration varied significantly depending on the distance from the mine tailings dam. A link between element concentration and the sampling site distance from the mining tailings dam was confirmed using a post hoc study of the Mann-Whitney U-test. This link raised concerns about the rising dangers of trace elements to human and ecosystem health. A metal contamination index also revealed a link between element concentrations in groundwater and the distance between sample locations and the mine tailings dam. Throughout the study, there was consistent evidence that high levels of trace elements in the mining environment were influenced by mining activities. However, there was a lack of background data of a specific area other than the international standards of which the researchers could make a comparison of their findings to make a sound environmental and human health problem conclusion.

2.4 Environmental Natural Radioactive Elements

Naturally occurring radionuclides, mainly ^{40}K, ^{232}Th and ^{238}U are the most common source of elevated radioactivity in all environmental components, including soil, water and air (Canbazoğlu & Doğru, 2013; Kapdan *et al.*, 2011; Wang *et al.*, 2015). These natural radionuclides have a high contribution to the ionizing radiation on Earth. ^{232}Th and ^{238}U contribute approximately 83% of the total exposure to people, whereas nearly 16% of the exposure is due to the primordial radioisotope ^{40}K, and the remaining 1% is contributed by the artificial sources of radionuclides (Asaduzzaman *et al.*, 2015; Dartnell *et al.*, 2007). Natural radionuclides from the environment are usually transferred to the human body through various routes such as ingestion, inhalation, and dermal contact (Alrefae & Nageswaran, 2013; Charlesworth *et al.*, 2011; Peter W, 2002). Approximately one-eighth of the total doses of natural radioactive materials have been reported to be attributed to the ingestion route (Awudu *et al.*, 2012). Furthermore, the inhalation and dermal contact pathways still contribute significantly to the human exposure dose globally, especially in mining areas (Ogundele *et al.*, 2021; Zhou *et al.*, 2020). As a result, radiation exposure of the human body due to radionuclides from ingestion, inhalation, and dermal contacts is of worldwide concern (Alrefae & Nageswaran, 2013; Asante-Duah, 2002; Haji-Saeid *et al.*, 2010). However, anthropogenic activities such as mining are constantly changing the geochemical cycles and biochemical balance of radioactive elements in the environment (Liu *et al.*, 2020). These changes gradually lead to an incremental dose that has negative health effects on people.

2.4.1 Natural Radioactivity in the Mining Areas

Different studies have demonstrated that human activities such as mining can result in situations where radiation levels from materials containing natural radionuclides increase to the point where regulatory control is required (IAEA, 2005; UNSCEAR, 2000). As a result, one of the most pressing fields of research is environmental intensive care and radiation safety. Radionuclides can build up in aerosols, damage land, water, and food, and eventually reach the human body. Radionuclides can bioaccumulate in several organs of the human body, posing a health risk. Long-term exposure to radioactive elements has been associated with haemorrhage, premature aging and mortality, shortened lifespan, leukemia, anemia, cancer risks, and cardiovascular problems in humans (Knoll, 2000). The risk of cancer from low doses of ionizing radiation has been the subject of a long-standing debate in the field of radiation protection (Korblein & Hoffmann, 2006).

Gold mining is related to high levels of radiation, mainly from ^{238}U, ^{40}K, ^{232}Th and their daughters (UNSCEAR, 2020). Different authors (Kamunda *et al.*, 2016; Malanca *et al.*, 1993; Ntihabose, 2010) have reported elevated concentrations of ^{226}Ra, ^{232}Th and ^{40}K above the world average in gold mine samples from South Africa, Brazil and Rwanda, respectively, while higher levels of radioactivity have also been reported in soil around Tanzania's Mkuju uranium deposit (Mohammed & Mazunga, 2013). The literature also demonstrated that gold mine tailings have significantly higher concentrations of ^{226}Ra, ^{232Th} and ^{40}K than typical soil (Esiole *et al.*, 2019; IAEA, 2007). This means that unmonitored gold mining waste could be significant sources of exposure to naturally occurring radionuclides for people living near and within gold mining sites.

The ASGM research by MbetAmos *et al.* (2020) on natural radionuclides ^{40}K, ^{232}Th, ^{238}U and ^{226}Ra in soil, rocks, and sediment samples from Zamfara State in Nigeria using gamma ray spectrometry techniques revealed that the average activity levels of ^{40}K, ^{232}Th, ^{238}U and ^{226}Ra in soil were 380.34 ± 116.41 Bq/kg, 151.15 ± 21.09 Bq/kg, 41.60 ± 11.06 Bq/kg and 37.94 ± 6.01 Bq/kg, respectively. The activity in sediments and rocks was also investigated, revealing higher values in rock samples; with external and internal hazard indices of 1.53 and 1.35, respectively, values greater than unity indicating a high level of risk. The radioactivity level index was 3.24, the gamma dose rate was 221 ± 35 nGy/h and the mean radium equivalent was 499.18 Bq/kg. The annual effective dose equivalents for indoor and outdoor environments were 985.39 μSv/y and 271.03 μSv/y, respectively. The mean lifetime cancer risks for outdoor and indoor soil were 2.18×10^{-3} and 0.55×10^{-3}. The assessment of the radiological health risk revealed that the values obtained were higher than the permissible limits and the world mean values (UNSCEAR, 2020). Mbetamos *et al.* (2020) concluded that the ASGM contributed significantly to the elevated levels of radionuclides and that people working and living within and near the mining area were at a high risk.

In southern Nyanza in the Migori ASGM in Kenya, Odumo *et al.* (2011) estimated the radioactivity levels of ^{40}K, ^{228}Th and ^{226}Ra from dust samples trapped within the crushing sites using NaI(TI) gamma-ray spectrometry method. The activity means ranged broadly from 80 to 413 Bq/kg for ^{40}K, 12 to 145 Bq/kg for ^{232Th,} and 21 to 258 Bq/kg for ^{226}Ra. In the air, the estimated absorbed dose rate ranged from16 to178 nGy/h and had an average value of 42 nGy/h. On the other hand, dust loading ranged from 1.3 to 3.7 mg/m^3. These results suggest that the ASGM practices were generally unsafe even if the activity levels of the radionuclides and the estimated annual absorbed doses were lower than the global permissible limits, the dust concentration at the mining site was high. For the inhalation route, Odumo *et al.* (2011) concluded that the health of ASGM workers was at risk. Based on the findings of these authors, there is evidence that mining activities, especially the ASGM sector, influence the levels of respiratory and other health problems within and in the vicinity of mining areas. Nonetheless, radioactivity is site-specific and depends on the geology and seasonal climate of an area. Therefore, it is very difficult to generalize the contamination of an area and the associated health effect on people according to international standards. A sound conclusion on the effect of radionuclides on the people and environment should be drawn by comparing the results with baseline data of an area prior to the project in which similar condition prevail.

2.4.2 Natural Radioactivity and Health Risk

Many studies have been executed in different areas across the world to assess the radioactivity levels in several mining areas (Asaduzzaman *et al.*, 2015; Awudu *et al.*, 2012; Odumo *et al.*, 2011; Zhou *et al.*, 2020). Also, determining the health hazards including the radiation dose received by the residents working and living within and near the mining areas has been done. In the small-scale mining sector, the ingestion of soils from the mining areas, inhalation of dust and radon gas and frequent contact with the soil and mine water during the washing activities in the gold recovery processes have been addressed.

Ademola and Obed (2012) reported the activity levels of radionuclides ^{226}Ra, ^{232}Th and ^{40}K in soil samples from the mining sites in the South-West of Nigeria using gamma-ray spectroscopy with NaI (Tl) detectors. The study revealed significant levels of radioactivity for ^{226}Ra ranging from 16.8 ± 1.6 to 71.1 ± 2.53 Bq/kg, ^{232}Th (3.0 ± 0.7 – 31.9 ± 1.0 Bq/kg) and ^{40}K ranging from 123.7 ± 3.8 to 1372.3 ± 8.6 Bq/kg. The study also reported values for the equivalent activity of radium in the range 74.2–121.0 Bq/kg. Furthermore, values ranging from 0.3 to 0.4 were reported for the internal hazard indices and from 0.2 to 0.3 for the external hazard indices. The annual effective dose was reported varying from 70.3 ± 13.5 µSv/y to 100.8 ± 42.8 µSv/y with an average of 87.5 ± 18.6 µSv/y. While there has been much information on the radiological hazard levels, the researchers did not take into consideration the levels of exposure based on the gender and age groups.

Kamunda *et al.* (2016) reported the radiological hazards due to the NORMS from the province of Gauteng in a South African mining site from 56 soil samples using gamma spectroscopy technique. The activity levels in Bq/kg for ^{40}K, ^{232}Th and ^{238}U from the mine tailings revealed to have values 427.0 ± 13.1, 43.9 ± 1.0 785.3 ± 13.7, respectively. The mean levels in Bq/kg for ^{40}K, $^{232}Th,$ and ^{238}U of the control area were 496.8 ± 15.2, 22.2 ± 0.5 and 17.0.1 ± 0.4, respectively. The estimated mean values for the internal hazard (H_{in}) and the external hazard (H_{ex}) of the mine tailings were found to be 4.5 and 2.4, respectively. These reported values were about 5 and 2 times, respectively, higher than the recommended world average values (UNSCEAR, 2020). All these values alerted for a substantial health risk to the residents. Kamunda *et al.* (2016) revealed consistent evidence that gold mining activities influenced radioactivity levels and posed significant health problems to the environment and the public.

Osoro *et al.* (2011) studied the radioactivity levels in the area planned for mining activities in Maumba and Ngauluku in Kenya using an HPGe gamma spectrometer. The mean activity reported for ^{40}K, ^{232}Th and ^{226}Ra, were 69.5 ± 16.5, 27.6 ± 9.1 and 20.9 ± 7.6 Bq/kg, respectively. These concentrations were used to estimate the absorbed dose rates in air with results ranging from 9.8 to 50 nGy/h, having a mean value of 29.2 nGy/h. These values were lower than the global mean (UNSCEAR, 2020). Therefore, these results had to be marked as the radiation background of an area and they were recommended to be used when planning proper surveillance and monitoring guides.

Radionuclides ^{238}U, ^{232}Th and ^{40}K were investigated from 20 water samples and 30 soil samples from the proposed Mkuju uranium deposits in Tanzania using low-level gamma spectrometry (Mohammed & Mazunga, 2013). The average activity levels of ^{238}U, ^{232}Th and ^{40}K in soil were found to be 51.7 Bq/kg, 36.4 Bq/kg, and 564.3 Bq/kg, respectively. These values were higher than the recommended world averages (UNSCEAR, 2020). Also, the water samples had the mean activity of ^{238}U (2.35 Bq/L) and 1.85 Bq/L for ^{232}Th. This study indicates that areas with uranium-rich rocks are expected to have high levels of radionuclides. Gold ores are believed to contain a significant phosphate and uranium content (Zhang, 2014). Therefore, ASGMs are expected to have significant levels of uranium and its decay daughters.

2.5 Radon Gas and its Progenies

The noble radon gas (^{222}Rn) is created in the radioactive decay of ^{226}Ra of the ^{238}U decay chain. The ^{222}Rn gas can easily escape from uranium-rich soils and rocks into the surrounding environment (Rowan & Kraemer, 2012). The inhalation of ^{222}Rn gas from closed locations such as mines and poorly ventilated buildings is the typical route of exposure. When ^{222}Rn decays, a sequence of short-lived daughter radioisotopes is produced (Rowan & Kraemer, 2012). Most inhaled ^{222}Rn is quickly expelled due to its chemical inertness, whereas its daughters may accumulate in the respiratory airways. The ^{218}Po and ^{214}Po, two of ^{222}Rn daughters, emit alpha particles (Richardson *et al.*, 1991). When this occurs in the lungs, the radiation can harm the cells that line the airways, potentially resulting in cancer. Although the nuclear breakdown of radon products releases energy in the form of beta particles and high-energy photons, the biological harm caused by these emissions is considered minor in comparison to the effects of alpha particles (Richardson *et al.*, 1991).

Many studies have been carried out to determine the levels of ^{222}Rn in homes and mines (Anderson, 2019; Appleton, 2013; Gillmore *et al.*, 2001; Guilmette *et al.*, 1991; Kumar *et al.*, 2010; Mlay, 2014; Mudd, 2008; Rowan & Kraemer, 2012; Sathish *et al.*, 2012; Speelman *et al.*, 2006; Tung, 2001; WHO, 2009; Wrixon *et al.*, 1984). Literature sources discuss a wide range of factors that influence radon uptake in homes and work places (Mudd, 2008; Nsiah-Akoto *et al.*, 2011). Ventilation, occupancy factor, people's living behavior, radioactivity concentration in construction materials, and room size are all factors to consider (Mohammed & Focus, 2018). Although the literature discusses these characteristics in a range of contexts, the focus of this study was on their impact on indoor radon levels in homes and mining pits.

2.5.1 Indoor Radon Concentrations

The indoor progeny of ^{222}Rn, thoron (^{220}Tn), and ^{220Tn} were explored by Ndjana *et al.* (2019) using RADUET detectors and TnP monitors at the gold mining sites of Betare-Oya, eastern Cameroon. The arithmetic means of the concentrations of ^{222}Rn and ^{220Tn} were 133 ± 39 and 93 ± 76 Bq/m^3, respectively, with a range of 88 – 282 and 4 – 383 Bq/m^3. For the ^{222}Rn and ^{220}Tn, 76% of dwellings exceed the WHO recommended level of 100 Bq/m^3, just 3% of houses exceed the International Commission on Radiation Protection (ICRP) threshold of 300 Bq/m^3. With a mean value of 6 ± 4 Bq/m^3, the equilibrium equivalent concentration of ^{220}Tn ranged from 1 to 19 Bq/m^3. The equilibrium factor of ^{220}Tn ranged from 0.01 to 0.55, with an arithmetic mean of 0.11, which was greater than the UNSCEAR global average value of 0.02. ^{222}Rn, ^{220}Tn and their progeny had a total inhalation dose ranging from 1.8 to 6.2 mSv/y, with an arithmetic mean of 3.8 ± 1.1 mSv/y.

Furthermore, according to a study by Kamunda *et al.* (2017) ^{222}Rn is omnipresent in the environment and comparable in most places on earth, but its concentration varies significantly in specific areas. Anthropogenic activities, such as mining, were frequently blamed for the unusually high values of indoor radon in workplaces. Despite reasonably effective mining operations, substantial levels of ^{222}Rn were discharged into the air and water, creating a legacy of environmental contamination that poses a health risk to the surrounding community. Because ^{222}Rn is the daughter of ^{238}U, it was frequently found in larger amounts around uranium ore deposits. Uranium has been the main source of concern in the gold mining districts of South Africa's Gauteng Province. Using the Alpha Guard radon professional monitor, Kamunda *et al.* (2016) detected significant levels of indoor radon gas in mine houses in a gold mining. Radon was also measured in a control area that was geologically similar to the mining environment. Indoor radon activity concentrations from houses in the mining area ranged from 1.0 to 472.0 Bq/m^3, compared to 0.1 to 35.0 Bq/m^3 in the control area. Annual effective doses corresponding to activity concentrations ranged from 0.03 to 11.89 mSv, with 3.01 mSv being the mean. Compared to the results of the control area, this average value was higher (Kamunda *et al.*, 2016). The average annual effective dose of radon was also higher than that reported for normal places around the world, indicating a potential health risk to the area's residents.

Between November 2010 and April 2011, radon concentrations and effective exposure doses were measured in 60 interior structures in the Tororo and Busia districts, eastern Uganda, using activated charcoal canisters and a sodium iodide detector (Biira *et al.*, 2014). The purpose of the study was to determine the radiological risk of exposure to radon (Biira *et al.*, 2014). The authors reported the effective dose ranging from 0.71 ± 0.03 to 2.44 ± 0.13 mSv/y, with ^{222}Rn concentrations ranging from 281 to 975 Bq/m^3. Overall, the mean radon concentrations recorded were all below the 200 Bq/m^3 ^{222}Rn action threshold suggested by UNSCEAR (UNSCEAR, 2020) and the ICRP (ICRP, 2019). Some average ^{222}Rn concentrations were close to the WHO's recommended action threshold of 100 Bq/m^3 (WHO, 2011). This indicates that ^{222}Rn levels were still within acceptable limits; however, the researchers could not suggest essential mitigation measures that could be implemented to ensure that ^{222}Rn levels do not exceed the mean values reported in their study. Also, it is statistically insignificant to conclude about the risk in an area of a district by comparing the risk with the world average. The baseline information and the control data may help in making a sound conclusion.

2.5.2 Indoor Radon Concentrations Vs. Building Materials

Due to the linked factors that may influence ^{222}Rn buildup in houses, the level of ^{222}Rn in houses is site-specific and complex. Even houses that are near to each other can have considerable differences in ^{222}Rn levels. These variances are linked to several factors including the amount of ^{222}Rn in a certain area, the type of the house, and the ^{222}Rn dilution ventilation status. Different building materials, such as soil, cement, sand, timber and stone, contribute to ^{222}Rn concentration levels in different ways. Badhan *et al.* (2012) investigated indoor ^{222}Rn levels in homes in the Kulu area of Himachal Pradesh, India. The average indoor concentration of ^{222}Rn in the investigated villages revealed values of 156.11 Bq/m^3 in the Kasol village, where buildings were built of wood, and 635.42 Bq/m^3 in the Balsavi village, where houses were built of rock pieces. The findings further showed that rocks rather than woodlands contributed more to the average indoor ^{222}Rn level in the settlements. In line with the findings of Badhan *et al.* (2012), Yousef *et al.* (2015) conducted a study in various areas of Egypt to determine the concentration of ^{222}Rn in various building materials, and came up with the following results in Bq/m^3: Sand ranged from 178.68 - 349.77, stones ranged from 359.98 - 366.46, clay soil ranged from 43.95 - 108.71, and bricks ranged from 65.64 - 152.83.

Amasi *et al.* (2015) investigated the ^{222}Rn and radium (^{226}Ra) exhalation rates of various building materials in Tanzania and found that clay soil had a high exhalation rate of ^{222}Rn of 1012.3 Bq/m^3 while gypsum samples had a low quantity of 27.3 Bq/m^3 (Table 1). The results in Table 1 indicated clearly how houses constructed using soil especially that taken from mining pits in ASGM areas may result to high levels of radon and other radionuclides.

Table 1: Different levels of ^{222}Rn and ^{226}Ra concentrations of building materials in Tanzania

^{222}Rn in Bq/m^3	^{226}Ra in Bq/kg	Material
1012.3	91.0±1.3	Clay soil
134.9	60.7±2.7	Rhino cement
56.7	25.3±0.7	Sandstone
308.9	55.8±4.3	Tembo cement
38.3	29.7±4	Kilwa cement
71.6	38.3±3.9	Samba cement
27.3	7.6±0.4	Gypsum

Amasi *et al.* (2015)

2.5.3 Radon Levels in Relation to Distance from the Contaminated Sites

Ivanova *et al.* (2014) conducted an indoor ^{222}Rn research in three villages in the former mining region of Bulgaria. The concentrations of ^{222}Rn in the dwellings ranged from 125 to 400 Bq/m^3. The 125 Bq/m^3 concentrations were reported from a village that was far from the mine, while the 400 Bq/m^3 concentrations were from a village that was in proximity to the mine. Public health being one of the global Sustainable Development Goals (SDGs) emphasizing on the good health and well-beings in the living and working environment (Tomás *et al.*, 2016), the working environment at different ASGMs in Tanzania seem to act contrary to the SDGs vision. This might slow down the efforts made by the Tanzanian government to attain the SDGs. Therefore, this necessitates a study of indoor radon levels in homes built in ASGMs areas.

Mlay (2014) conducted a study on indoor ^{222}Rn concentrations in eight villages in Manyoni district, Singida region of Tanzania, near a proposed uranium deposit. In Mkwese village, the average concentration was 43 Bq/m^3, while in Majengo, it was 377 Bq/m^3. Because Majengo village was closer to the deposit, the value in Majengo village was greater than the WHO recommended value of 100 Bq/m^3 (WHO, 2011). Moreover, a study done by Mohammed and Focus (2018) in Bahi district, Tanzania, revealed that Bahi Makulu village, which was close to the deposit had houses with high levels of ^{222}Rn gas compared to another village (Bahi Sokoni) which was about 7 km from the deposits. These findings indicate that ^{222}Rn concentrations indoors are high in places close to mineral deposits or in places where anthropogenic activities such as mining take place. The COVID-19 pandemic has changed the lifestyle of many people including those that live in isolated rural communities. The lesson from COVID-19 has been that public health matters to all. The importance of precautions, prevention, and protection-even against radiations cannot be overemphasized.

2.5.4 Radon Levels and Ventilations Structures

Radon levels appear to be higher in enclosures than in open settings. This was demonstrated by Kumar *et al.* (2010), who conducted a study on ^{222}Rn concentrations in various homes near the Taj Mahal in Agra, India. The ^{222}Rn concentrations ranged from 98 to 305 Bq/m^3, with an average of 213 Bq/m^3 in kitchens and bedrooms and 148 Bq/m^3 in open areas such as broad corridors and living rooms with large windows. The results of a study conducted in Bahi, Tanzania, by Mohammed and Focus (2018) on levels of indoor ^{222}Rn concentration in traditional ("*tembe*") and modern houses back up these findings. Compared to modern houses, the "*tembe*" houses were inadequately ventilated and had higher levels of radon compared to modern houses. Furthermore, the findings revealed that the indoor concentrations of ^{222}Rn in 78% of the houses studied were above the 100 Bq/m^3 guideline (IAEA, 2007; WHO, 2011). Traditional dwellings, which are generally designed with poor ventilation, usually have higher levels of radon than modern houses with good ventilation structures. Apart from the fact that ventilation structures do influence the levels of fresh indoor air, climate change has also significantly contributed to fresh air problems (D'amato *et al.*, 2016; Kinney, 2008). It should be noted that human activities, including mining, have contributed significantly to climate change (Wiston, 2017). Climate change has a significant impact on air quality. Taking into account the impacts of climate change and the exacerbated air, water and soil quality due to human activities; it is imperative that indoor air quality be controlled in dwellings close to mining sites.

The radiation safety of the Abu Tartur open-pit phosphate mine and subterranean tunnels in Egypt was investigated by Dallal *et al.* (2020). The ^{222}Rn and ^{220}Tn progeny were measured in samples collected from 31 sites representing the phosphate mining area. In the case of open-pit mining, the results of ^{222}Rn, ^{222}Rn daughters and ^{220}Tn daughters ranged from 1.37 to 131.52 Bq/m^3, 0.000099 to 0.0024 WL and 0 to 0.92 Bq/m^3, respectively (Dallal *et al.*, 2020). The ^{222}Rn, ^{222}Rn daughters and ^{220}Tn daughters ranged from 411.55 to 2539.27 Bq/m^3, 0.056 to 0.37 WL and 1.26 to 3.89 Bq/m^3, respectively, for the tunnels. Gamma radiation levels, surface pollution, and the annual effective dose were also measured. Gamma radiation levels in open-pit mines varied from 0.07 to 0.6 mSv/h, whereas the tunnels had levels ranging from 0.24 to 0.5 mSv/h. For open-pit mining, surface contamination values were minimum, and for underground mining, they were 7.1 mSv/h. The effective annual dose for open pits ranged from 0.033 to 0.153 mSv/y, while the tunnels revealed 4.948 mSv/y. The results for open pit mines were lower than the allowed levels established by UNSCEAR (2020), whereas the results for subterranean tunnels exceeded the permissible limits (UNSCEAR, 2020). As a result, open-pit mining is extremely beneficial in terms of occupational radiation protection.

2.5.5 Radon Levels Vs. Room and Pit Volume

The association between the levels of ^{222}Rn concentration and the volume of the room under investigation was shown by Sathish *et al.* (2012) on the assessment of ^{222}Rn and ^{220}Tn levels in dwellings in Bangalore City, India. Sathish *et al.* (2012) discovered that small rooms had higher ^{222}Rn concentration than large rooms. The concentrations in residences with volumes ranging from 20 m^3 to 31 m^3 ranged from 93 to 4 Bq/m^3, respectively, among the 42 rooms studied at each site. The concentration of ^{222}Rn appeared to decrease exponentially as the volume of the room increased, and it appeared to remain nearly constant at 150 m^3. The size of the room has an impact on occupational and public health. This has been proved during the COVID-19 pandemic, where social distance was one of the determining factors in the fight against the pandemic.

The international dimensions for a standard room are suggested to be at least 4×5×2.8 (56 m^3) (L × W × H), where L is the length, W is the width and H is the height of the room (European Commission, 1999). The European Commission (1999) further suggested that the dimensions of the door (s) and the window (s) of the standard room be 1×1.8 and 1.4×1.4 (W×H) meters, respectively. Small rooms being at home or at workplace influence more to the effects of occupation health. This has been widely proved by many people throughout the world during the COVID-19 pandemic, where fresh air was one of the determining factors in fighting the pandemic. Therefore, some of the preventive COVID-19 practices should be extended to all occupational health risk control.

The dimensions of the mining pits in the ASGM industry are not established. The size of the pit depends on the decision of the miners in a place. Also, the economic stability of the miners defines the size of the mining pits. However, the national and international documents are silent on the specific dimensions and structures of the mining pits in the ASGM sub-sector.

2.5.6 The Occupancy Factor

The occupancy factor refers to the level of human possession of an area closest to a source of radiating material (Adagunodo *et al.*, 2019; Anderson *et al.*, 2002). The occupancy factor plays a crucial role in determining the value of exposure to ^{222Rn} and the dosage of the measured concentration (Bq/m^3) and must be established. The UNSCEAR (1993) suggested an indoor value of 0.8 as the global average occupancy factor, assuming that people spend roughly 19 hours of each day in a suspectable area. But the occupancy factor varies by location and by type of persons, also by whether the exposure is in residents (indoor) or at a working place such as in mining pits. According to Wrixon *et al.* (1984), northern countries appear to have a high indoor occupancy factor of more than 90% (0.9). In northern countries, people spend roughly 21.5 hours each day indoors (Wrixon *et al.*, 1984). This is due to the environment conditions in the countries, such as cold weather, which causes people to stay indoors for extended hours.

Anderson (2019) found that the occupancy factor for women in France is 0.9, due to the fact that women in France spend more time at home than men. In Ghana, Nsiah-Akoto *et al.* (2011) employed an occupancy factor of 0.4, which was derived based on the fact that in Ghana, people spend roughly 9 hours out of 24 hours a day indoor. This was in accordance with the local climate.

The working environment in the ASGM sub-sector especially in the sub-Sahara African countries has no defined rules and regulations regarding working hours (Mutagwaba *et al.*, 2018; Mwaipopo *et al.*, 2004). For example, a field observation in two ASGM namely, Buhemba and Rwagamasa in Tanzania revealed men working in mining pits consistently for about 13 hours, others working for extended time up to 20 hours. This is contrary to the suggested working time by ILO (2005) of 8 hours per day. It is therefore important to develop the occupancy factors basing on gender, age group and people's habits in a particular study area. This might help in concluding relevant health risk.

2.6 Artisanal and Small-scale Mining and Artisanal and Small-Scale Gold Mining: A Policy Perspective

Hilson (2006) investigated the policy methods used in the reduction of Hg contamination in the ASGM sector in Latin America, sub-Saharan Africa and Asia. Hilson (2006) argued on the way these policies in the mentioned regions are framed in supporting the health of workers and the public. The researcher emphasized that, although these issues have piqued the scientific community's interest in the last 30 years, subsequent research has failed to uncover appropriate mitigation methods and has made little progress in understanding why pollution continues. Furthermore, the tactics employed to educate operators and the public about the dangers of acute Hg exposure, as well as the technologies used to prevent future pollution, have been shown to be ineffective at best. Hilson (2006) found that governments and donor agencies will not be able to fix the Hg contamination problem until they commit to conducting critical scientific research to better understand the dynamics of small-scale gold mining communities. The researcher concluded by advising the governments and stakeholders to use the knowledge of experts in policy frameworks to fight the problem of Hg in the ASGM sub-sectors. This argument is applicable in the Tanzania ASM/ASGM environment because environmental and human health problems have been frequently reported without an end solution.

The ASGM sector in Brazil generates about 6 tons of gold (Au) each year and employs more than 200 000 people (Sousa *et al.*, 2011). Most of these gold mining activities take place in the Amazon, where miners have been extracting gold for almost 40 years. The authors report however, that about 99% of miners in the Tapajos River Basin operate without the environmental and mining licenses required by law. This was due to a combination of ineffective or unrealistic policies and regulations, a lack of political will, insufficient infrastructure to enforce current regulations, and a lack of incentives for miners (Sousa *et al.*, 2011). In their study, 20 groups of Brazilian laws, policies, decrees, and resolutions, concentrating on how the regulations coincidences expose gaps between policy and reality in ASGM domains were reviewed.

Apart from gaps obtained from these documents, also it was found that the Brazilian government lacks the resources such as well-trained people, vehicles, up to date information, and supplies to enforce the rules because the ASM operate in vast and isolated locations. Sousa *et al.* (2011) findings further highlighted on the importance of establishing new government commitments and defining priority regions for government agencies to concentrate their efforts. Moreover, it was clearly seen from (Sousa *et al.*, 2011) study that there was no single answer to the ASGM-related environmental, health, technical, and socio-economic issues. The authors concluded by emphasizing on a practical strategy that should aim at raising miners' educational levels regarding radioactive and heavy metals health effects especially Hg, establishing government programs to provide technical support in the ASGM field, financial support to the ASGM-miners for sustainable improvement, and providing effective enforcement measures.

Furthermore, Spiegel (2009) studied the policy framework of ASGM in Zimbabwe. The author's report contends that the primary government measures to supervise gold mining had proven unproductive, as the economic returns of minerals had decreased due to increased illegal activity. The authority's reluctance to take an all-stakeholder approach to develop adequate resource policies had harmed the sector's productivity and worsened the existing situation. The author concluded by emphasizing on a major policy restoration, with a focus on improving access to fair gold pricing, providing technical help to vulnerable workers, especially in the ASGM sector, and streamlining regulatory institutions.

While studies looking at the nature and impact of gold mining in Ghana have identified environmental degradation as a major consequence of resource extraction, only few studies have examined the challenges and opportunities that come with implementing environmental policies in Ghana's gold mining sector (Darimani *et al.*, 2013; Tuokuu *et al.*, 2018). Tuokuu *et al.* (2018) studied on the impacts and influences of policies, laws, and regulations on the gold mining sector in Ghana. It was revealed that little attention had been paid to the perspectives of key stakeholders that could be harnessed to enable efficient application of the present environmental rules in the gold mining sector. As a result, it was revealed that insufficient coordination among government institutions, lack of community participation, lack of political will and inadequate personnel and logistics, are all factors contributing to the ineffective implementation of environmental and mining policies in Ghana's gold mining industry. This observation is in line with the current situation in the mineral and mining policymaking process of Tanzania which lacks important aspects including community participation, involvements of all relevant stake holders and the inclusion of scientific findings (Tables 2, 3 and 4). Therefore, the emphasis on the theoretical and policy implications for the effective implementation of environmental and public health in Tanzania is important.

2.6.1 National-Level Environmental Regulatory Framework

The Tanzanian mining and mineral sector have a long history of policymaking. The gaps between mining policies, laws, regulations, and the environmental and public health in Tanzania ASGM/ASM subsector have been evidenced in many studies (Kinyondo & Huggins, 2021; Lissu & Mark, 2008; Ng'wanza, 2013; URT, 2010; Walwa, 2016). This has environmental, health, social and economic consequences for people who live near mining operations. It is estimated that in 2017 a total of 8800 ASM centers were registered and primary mining licenses (PML) were issued, and the government of Tanzania aims to register more 100 new small-scale mines by 2025, providing other 19157 PML (URT, 2021). The ASM subsector that employs more than 1.5 million people from rural areas of Tanzania supporting the livelihood of more than 9 million poor Tanzanians (URT, 2021) needs special attention in governmental policies, laws and regulations. In the present study, 27 documents related to minerals and mining sector of Tanzania have been analyzed and summarized in Tables 2, 3 and 4. It follows that the policies, acts, regulations, strategies, reports, and guidelines covering the broader issues pertaining to mining and mineral production in Tanzania have been analyzed.

(i) Policy Overview

In the present study, six policy documents (Table 2) were analyzed to identify the gaps between policies and realities on the ground in the ASM/ASGM environments in Tanzania. Among many policies in Tanzania, the five selected policies have a close link between the mining industry, the environment, public and occupational health. It was clearly noted that 80% of the policy documents analyzed did not directly cover issues related to ASM/ASGM (Table 2). These policies lacked important aspects such as national radiation levels and dose limits, public health, and protection from the ionizing radiations, occupational health, environmental pollutions, public health education and awareness on mine wastes, technical supports and hazards related to radiation exposure. These realizations highlight the importance of establishing the national radiation background and doses, government commitments, and defining priorities for policy review. On the other hand, a practical strategy should involve the following aspects: (a) raising the awareness of the miners about matters relating to mining hazards, (b) establishing government programs to provide in-field technical support, (c) using information-based strategies to encourage sector-wide improvements, unionization, and community involvement, (d) encouraging social organization of gold miners, (e) strengthening small-scale worker groups, micro financial institutions to raise capital to support sustained improvements, and (f) offering effective enforcement measures.

Table 2: Summary of main policies influencing ASM/ASGM in Tanzania

Policy	Issues of ASM/ASGM	Reference(s)	Remarks/shortcomings
1. The Mineral Policy of Tanzania (2009)	Support and development of ASM are addressed in this Policy. For example, the objective of the Policy (f) in Section 5.6 states "*To promote and support the development of ASM to improve its contribution to the individual and national economy"*. Also, the Policy states the need for the government to collaborate with stakeholders in the ASM sector to preserve the environment. Also, 'The *need for technical services to the ASM sector'* is emphasized in Section 7.3 of the Tanzanian Mineral Policy.	(URT, 2009)	The Policy lacks some important aspects such as 1) environmental exposure 2) occupational exposure 3) mercury toxicity and 4) mercury exposure which are frequently reported in the ASM/ASGM working environment. This policy needs to be revised and important aspects of ASM/ASGM be included.
2. National Forest Policy (2008)	Section 1.1.2 informs that the mining sector is one of the main economic sectors in Tanzania. However, Sections 1.3.2 and 2.3 of the National Forest Policy named the mining sector among the rapidly expanding human economic activities that contribute to severe environmental degradation. Still, having pointed out mining as an important economic sector in Tanzania, it does not include the issues of the ASM/ASGM subsector, which is rapidly growing in Tanzania and is frequently reported to contributing to environmental pollution and deforestation.	(URT, 2008)	Because the ASM/ASGM is a fast and rapidly growing subsector that has been frequently reported to contribute to deforestation, there is a need to revise this policy and include the issues of land degradation in the ASM/ASGM environment which will help to safeguard the environment against unsafe mining practices by artisanal and small-scale miners. In addition, the forestry and mining sectors need to work together during policy development.
3. National Land Policy (1997)	Objective 2.2 of the National Land Policy recognizes that "*small holders such as peasants and herdsmen who are the majority of the Tanzanian population have all the rights to land ownership.*" However, the Policy barely includes the fast-growing ASM/ASGM subsector. Furthermore, there are general provisions on health effects resulting from animal keeping and cultivation on hazardous lands, preventing buildings on hazardous lands, and protection of risk groups such as children in hazardous areas.	(URT, 1997)	The National Land Policy needs to be revised because the ASM/ASGM has been reported to have conflicts with the neighboring communities on issues of land allocation, acquisition, and use. There is a need to have a clear definition of land ownership in the sphere of artisanal and small-scale mining. Therefore, issues of the ASM/ASGM and mining in general should be included in this Policy.
4. National Occupational Health and Safety Policy (2009)	The National Occupational Health and Safety Policy statements ii-iv emphasizes on the need of the government and all stakeholders "*to develop occupation safety and health standards, to ensure occupational health and safety compliances for the military installations, and to conduct awareness campaigns to gear the safety*	(URT, 2009)	The health and safety issues in the ASM/ASGM subsector in Tanzania should be carefully addressed. This is due to the fact that this sub-sector is operated by people with small capital investment, but who can significantly contribute to the national GDP. In some cases, the rural

Policy	Issues of ASM/ASGM	Reference(s)	Remarks/shortcomings
	issues to the employers, workers and the community". It does not clearly address matters related to ASM/ASGM.		economy largely depends on this subsector. In such cases, it is mostly the women and youth who perform mining activities. Therefore, the Policy needs to be revised to include the issues of the ASM/ASGM such as radioactive and trace elements exposure as well as occupational safety.
5. The National Health Policy (2017)	Objective XX of the National Health Policy puts it clear that there is a need for safety and supportable health at workplaces. Objective XXII further emphasizes the need for environmental pollution and climate change control. The Policy, however, does not directly address issues related to ASM/ASGM.	(URT, 2017)	Environmental pollution and climate change have been frequently reported in the ASM/ASGM. These have contributed to human health problems in the ASM/ASGM working environment and surrounding communities. It is important for this Policy to include the issues of public health risk and hazards such as radionuclides occurring in the ASM/ASGM environment. Also, the National Health Insurance Fund (NHIF) may be introduced to the small-scale miners to make them access health services easily.
6. The National Nuclear Technology Policy (2013)	The Policy explains the use and advantages of nuclear medicine. Also, the Policy generally addresses some issues related to the sources of radiation due to NORMs and their implications specifically focusing on uranium mining. However, the ASM/ASGM subsector is not directly included.	(URT, 2013)	This Policy could include the issues of NORMs resulting from the ASM/ASGM environment. This is because the ASM/ASGM subsector is expanding rapidly and health risk due to NORMs is frequently reported in the sector.

(ii) Legislation Framework

The gaps between Tanzania's government acts and the ASM/ASGM subsector are revealed in Table 3. It is seen from Table 3 that 11 of the 12 acts analyzed were found to not directly cover ASM/ASGM issues. The silence in these acts may lead to missing important information on exposure from radioactive materials, a good working environment such as good ventilation in mining pits, environmental pollution, public health education and knowledge on mining waste management, offering technical support to miners, and access to protective gears.

Table 3: Summary of main Acts Affecting ASM/ASGM in Tanzania

Act	Issues of ASM/ASGM	Reference(s)	Remarks/shortcomings
1.The Mining Act 2010	CAP. 328 of this Act defines the ASM in terms of capital investment. And Part III explains the Board that advises the Minister on issues relating to mining. The Board includes one member from the ASM. The Act also gives the Minister power to regulate various mining issues. For example, Part X CAP. 188, Section 108 (5) states, *"The Minister shall make special regulations for the purpose of ensuring public safety and regulating mining, processing, hauling, transporting, conveying, marketing and disposition of radioactive minerals"*. However, this statement is inherently concerned with the LSM, especially dealing with radioactive metals such as uranium.	(URT, 2010)	Although the Act explains well the procedures of dealing with radioactive materials, it resides more with the LSM subsector, which deals with radioactive ores such as uranium. But the issues of radiation exposure in the ASGM must be given special attention due to the nature of the working environment. Therefore, future revisions of this Act and its regulations should include matters of public health in the ASM environment.
2.Public Health Act (2009)	Overall, the Public Health Act of Tanzania (2009) does not address issues related to ASM/ASGM. However, there is a general provision indicating hazardous and health care waste management.	(URT, 2009)	The public health issues in the ASM/ASGM and surrounding communities has recently become a global agenda. This could be due to the nature of the working environment. Therefore, health issues in the ASM/ASGM sub-sector in Tanzania must be given a special attention in laws and regulations. Hence, issues related to welfare of ASM/ASGM mining should be included in the next revisions. This might help to minimize the health risk in the subsector.
3.The National Wealth and Resources (permanent sovereignty) Act (2017)	The National Wealth and Resources (permanent sovereignty) Act does not address the issues in the ASM/ASGM sub sectors. However, it puts clear the ownership of the natural resources. Part II section 5 (1) of this act explains clear that *"the natural wealth and resources shall be inalienable in any manner whatsoever and shall always remain the property of the people of the United Republic"*.	(URT, 2017)	Mineral resources in Tanzania contribute more to the wealth of the nation and individuals. Recently the government of Tanzania has worked to improve the ASM/ASGM subsector due to its contribution to the nation GDP and in poverty lessening to the poor communities of Tanzanians. For these and other reasons, we suggest the inclusion of issues of the ASGM/ASM to this Act.

Act	Issues of ASM/ASGM	Reference(s)	Remarks/shortcomings
4.The Industrial and Consumer Chemicals (management and control) Act (2003)	The Act does not address the ASM/ASGM in Tanzania. But it addresses the storage of the chemicals in a way that, exposure to people is controlled.	(URT, 2003)	The use of mercury and cyanide in the ASM/ASGM subsector during gold recovery has been not only a nation issue but also a global agenda. Including the prohibition of using such chemicals in this Act might reduce the prevailing improper use of mercury and cyanide in the ASGM.
5.The Environmental Management Act (2004)	The Environmental Management Act of Tanzania does not touch on issues related to ASM/ASGM. However, the Act emphasizes the issues of safety in the working environment. For example, section 6 part (h) reads "*To have a plan to ensure the health and safety of the workers and neighboring communities*"	(URT, 2004)	The ASM/ASGM subsector in Tanzania has been frequently reported to contribute greatly to environmental pollution. Studies have evidenced that mining wastes from the ASM/ASGM pollute water, air, and soil. Because the ASM/ASGM is a fast-growing subsector, there is a need of having a special inclusion of the ASM/ASGM related issues in this Act.
6.The Forest Act (2002)	The Forest Act does not address issues on the ASM/ASGM. However, Chapter 18 section 1 and 2 talks about mining in general and the EIAs.	(URT, 2002)	The Act need to be revised and include issues of ASM/ASGM for example deforestation. The loss of vegetation and trees within and around the ASGM/ASM working areas have been reported to contribute to the climate change problem facing the world.
7.The Protection from Ionizing Radiation Act (1983)	The Protection from Ionizing Radiation Act does not say anything on ASM/ASGM. However, the Act addresses the importance of the government to give information and education to the people regarding radiations.	(URT, 1983)	The problem of radiation related diseases such as cancer have been frequently associated with mining activities especially to the ASM/ASGM subsector. Due to the nature of the working environment in the ASGM, it is suggested this Act to have a special attention and inclusion of the section governing the issues such as trace and radioactive elements in the ASM/ASGM.
8.The Land Act (2009) with its revision of 2019	The Land Act does not say anything on the ASM/ASGM. However, it covers problems regarding the hazardous land.	(URT, 2009)	Mining especially the ASM/ASGM subsector has been frequently reported to cause hazards to the environment. Therefore, future revision should include matters related to mining including land ownership and utilization which are often leading to conflicts among miners and other citizens.
9.The Occupational Health and Safety Act (2003)	The Occupational Health and Safety Act addresses the general effects of people exposure to ionizing radiation.	(URT, 2003)	Note that the current rapid growth of ASM/ASGM in Tanzania has resulted to the increase of the radiation related health risk to people especially workers. Therefore, the Act needs to have a

Act	Issues of ASM/ASGM	Reference(s)	Remarks/shortcomings
			special attention to the occupational health and safety to the ASM/ASGM working environment.
10. The Tropical Pesticides Research Institute Act (1979)	The Tropical Pesticides Research Institute Act is silent to issues of ASGM. But it addresses the general issues of the chemical hazards.	(URT, 2002)	Because the ASGM is associated with the use of different chemicals such as Hg and cyanide. There is a need to revise the Act and include regulations to deal with these chemicals in the ASGM sub-sector.
11. Atomic Energy Act (2002)	The Act lacks aspects of the ASM/ASGM. However, it explains the need for general radiations exposure protection.	(URT, 2009)	The aspects of the radionuclides in the mining environment have recently been not only a regional issue nut also a global topic of concern. A fast-growing ASM/ASGM subsector in Tanzania has evidenced through various studies radiation exposure risk. To minimize these effects, the Act needs revision while adding the issues of radioactivity in the ASM/ASGM.
12. Local Government (district authorities) Act (2009)	This Act covers various issues including rural development, economic activities and public health but it does not address issues of the ASM/ASGM.	(URT, 2009)	The ASM/ASGM has been a poverty lessening for the local community. The sector employs about 1.5 million local people and the life of about 9 million people depend on the sector. for this purpose, the local governments need to include the issues of ASM/ASGM in their by-laws. This Act needs to be revised to include the ASM/ASGM issues such as land pollution and ownership, and deforestation.

(iii) Regulations, Strategies and Guidelines

Despite the relative success of the regulations, strategies and guidelines in supporting the ASM/ASGM in Tanzania, these documents have not yet been followed as intended by Tanzania's mining policy (URT, 2009), the mining Act (URT, 2010) and the SDGs (United Nations, 2015). On the ground, these regulations, guides, and strategies on the are yet to address the environmental impacts and public health risk in the ASM/ASGM subsector. Additionally, one of the major criticisms of these official documents is the exclusion of the ASM/ASGM related issues. Table 4 shows eight analyzed official documents of which six documents do not directly cover matters related to the ASM/ASGM subsector. Furthermore, the documents that addressed the ASGM/ASM issues did not address the problems such as environmental pollution, human health risk, and deforestation facing the ASM/ASGM subsector.

Table 4: Summary of Main Regulations, Strategies and Guidelines Affecting ASM/ASGM in Tanzania

Regulation/Strategy/Guide/report	Issues of ASM/ASGM	Reference(s)	Remarks/shortcomings
1.Tanzania Mining Industry Investor's Guide (2015)	Section 6.1.5 emphasizes on the duty of the State Mining Corporation (STAMICO) to the ASM/ASGM. This section reads "*The State Mining Corporation (STAMICO) offers services to the mining industry such as contract drilling, resource assessment, as well as providing extension services to small scale miners*" It generally emphasizes on the need of a strong, well-organized, and vibrant ASM industry.	(URT, 2015)	It does not clearly specify the issues of health risk due to radiations and trace elements in the ASM/ASGM sector. it is recommended to include these important aspects in the guideline. This might help to reduce the frequently reported problems of environmental pollution and public health in the ASM/ASGM working environment.
2.The Atomic Energy (protection from ionizing radiation) Regulation (2004)	It is silent on the issues pertaining ASM/ASGM. However, it generally says on workplace hazards including radiations from NORMS	(URT, 2004)	The problems of ionizing radiations to the people working and living near the ASM/ASGM has recently been a global agenda. Tanzania having many ASM/ASGM centers face the same problem. It is advised to include a section of radionuclides facing the ASM/ASGM to this regulation.
3.The Atomic Energy (radiation safety in the mining and processing of radioactive ores) Regulations (2011)	These regulations cover the general aspects of mining. Issues such as radiation levels, and ventilations in the working places are clearly addressed. But the issues of ASM/ASGM, a fast-growing subsector in the mining industry are not directly addressed.	(URT, 2011)	The ASM/ASGM in Tanzania have been reported to have high levels of radiations above the backgrounds. Also, the issue of poor ventilated houses in the mining sites and poor ventilated mining pits are frequently reported in Tanzania ASM/ASGM sub-sector. Therefore, there is a need to have a special section to these regulations that address issues of ASM/ASGM.
4.Radioactive Waste Management for the Protection of Human Health and Environment Regulations (1999)	These regulations do not say anything on ASM/ASGM. These regulations cover the general environment on issues of waste management, radiation protection and health environment.	(URT, 1999)	Improper mining wastes management in the ASM/ASGM in Tanzania need a special attention. Studies have evidenced a continuous problem of environmental pollution and human health problems resulted from the improper mining waste management in the ASM/ASGM

Regulation/Strategy/Guide/report	Issues of ASM/ASGM	Reference(s)	Remarks/shortcomings
			sub-sector. This regulation needs to include issues of the ASM/ASGM.
5.The Atomic energy (protection from ionizing radiation) Regulation (2004)	These regulations address issues of ionizing radiation protection in radiotherapy. The ASM/ASGM is not addressed.	(URT, 2004)	Higher levels of radionuclides have been reported in the ASM/ASGM. The ASM/ASGM subsector involves mostly poor people and the most vulnerable people such as women and children. These groups need to be protected from ionizing radiations. These regulations need to be revised and issues of risk due to ionizing radiations due to ASM/ASGM activities should be included.
6.The Environmental Management (air quality standards) regulations (2004)	They are silent on issues of ASM/ASGM. These regulations cover areas such as manufacturing industries and traffics that emits dangerous gases such as carbon and carbon dioxide.	(URT, 2004)	Air pollution and air quality related diseases have been frequently reported in the ASM/ASGM working environment. The problem extends further to the surrounding communities. In order to reduce the problems, the air quality issues in the ASM/ASGM have to be strongly addressed in these regulations.
7.Inspection Manual for Small-scale Mines (2010)	The manual puts it clear that, for the ASM/ASGM, the EIA is not necessary for requesting the mining license. The most important thing is that before starting mining activities, the owner must conduct the baseline data on environmental research and social studies such as vegetation, water resources and presence of human settlements	(URT, 2010)	The manual explains very well on the need to have these baseline data. However, some of the miners do not do that important aspect. Therefore, there is a need to include a section of penalty in the inspection manual to those people who go against this aspect.
8.The Sustainable Management of Mineral Resources Project (SMMRP) Phase II	This report puts on the responsibility of the artisanal and small-scale miners. One of the arguments states, *"Small-scale miners have to conduct studies and prepare environmental management protection plan (EPP)".* However, this statement is not supported by any policy or law reviewed.	(MEM, 2015)	The ASM/ASGM employs people with low level of income and low capital investment. Also, the education background of these miners does not support the argument made in the report.

This analysis indicates that regulators in developing countries, including Tanzania, are probably influenced by concepts created in the developed world, which may lead to unrealistic governing laws in developing countries. This is evidenced in Tables 2, 3 and 4. Even objectives which are stated in some documents are hardly being practiced (Lissu & Mark, 2008; Walwa, 2016). For example, one of objectives in the Tanzania Mining Policy (URT, 2009) is to "*strengthen capacity for administration of the mineral sector; promoting and facilitating value addition to minerals; developing small-scale miners; and strengthening environmental management*". It is about 13 years past after the release of this Policy but the progress of the ASM/ASGM subsector is very slow (Mutagwaba *et al.*, 2018). Furthermore, the Tanzania Mining Industry Investors Guide (URT, 2015) supports the idea of the growth of the ASM sector in Tanzania. This was evidenced in one of its objectives, which read *'to provide well-established support to the ASM mining industry'*, giving the vision for the Tanzanian mining industry for 10 years, with the aim of having a vibrant, strong, and well-organized ASM subsector that is conducted in a safe and environmentally friendly manner. However, this is contrary to scientific findings that have frequently reported environmental pollution and public health risk in the Tanzania ASM/ASGM subsector (Focus *et al.*, 2021; Mutagwaba *et al.*, 2018).

The Mineral Policy, the Tanzania Mining Industry Investor Guide, the Small-Scale Mine Inspection Manual, and the Mining Act collectively provide the framework for the ASGM subsector in Tanzania. The Mineral Policy recognizes the role of ASGM to individuals and the national economy. Although, with the rapid growing of the ASGM sub-sector, and a broad lack of knowledge regarding the impacts of ASGM, the current Mineral Policy is weak in terms of providing a clear vision regarding environmental and public health risk in the ASM/ASGM. In particular, the current Mineral Policy does not clarify how ASM/ASGM can be practiced in parallel with the progressive aspects of the SDGs 3 and 8 that stresses *"the right to healthy lives"* and encourages *"well-being for all and endorsing sustained, sustainable, and inclusive economic development, full and productive employment and decent work for all"*, respectively (United Nations, 2015). This is attributable to the lack of enforceable and definite regulations to control the ASM/ASGM subsector in Tanzania. In the perspective of SDG8, it is essential to improve health and safety at ASM sites to achieve decent employment for everyone by creating safe and secure working environments. Poor safety precautions at ASM/ASGM sites have serious spillover effects on nearby populations in addition to directly affecting workers.

The Phase II Sustainable Management of Mineral Resources Project (SMMRP) requires ASM miners to conduct a study and prepare an environmental management protection plan before starting mining activities (MEM, 2015). This could be a challenge for Tanzanian ASM miners due to the education and economic status of people involved in the ASM/ASGM subsector. The majority of the ASM/ASGM-miners are primary school leavers and others are secondary school dropouts (Mutagwaba *et al.*, 2018; Mwaipopo *et al.*, 2004). People who are involved in the ASM/ASGM have insufficient capital to get experts to do the required studies.

It is clearly known that the challenges facing the ASM/ASGM in Tanzania are different from those facing the LSM (Maliganya & Bengesi, 2018; Mutagwaba *et al.*, 2018). This is due to the recognized differences between the ASM/ASGM and LSM. These differences include the capital invested, the tools used, and the experts employed in the sectors. Due to these recognized differences, it becomes difficult to address the ASM/ASGM and LSM issues and challenges in one document. The South African Government, for example, has a special policy dealing with the ASM/ASGM subsector (Department of Energy and Resources Mineral, 2021). Many issues pertaining to ASM/ASGM in South Africa are clearly integrated and defined in the Artisanal and Small-scale Mining Policy of 2021 (Department of Energy and Resources Mineral, 2021). The issues of health and safety, environmental management, water and land use and management, financial provisions requirements are all clearly defined in the South African ASM Mining Policy. In addition, the Government of Ecuador has developed a special regulatory rule for ASGM which defines separate regulations applying to artisanal and, small-scale mining industry and create strategies for increasing training programs to encourage justifiable progress of the ASGM subsector (Ecuador Government, 2015; Miserendino *et al.*, 2013). The Ecuadorian regulations for the ASGM is supported by the Mining Act which broadly take into consideration the ASM/ASGM subsector. For example, Art. 6 of the Ecuadorian mining Act says:

> *The state shall establish technical assistance, training, promotion, and financing mechanisms for the sustainable development of ASM. It shall also establish incentive systems to support the environment and to generate a more efficient production unit*

The governmental support to the ASM subsector in terms of machinery is also extended in Chapter IV Art. 45:

> *For small-scale mining, the state shall authorize the operation of mineral beneficiation. Plants constituted solely for crushing and grinding purposes, with installed capacity*

of 10 tons per day, and beneficiation plants that include crushing, griding, flotation, and/or cyanidation capabilities with a minimum installed capacity of 50 tons per day.

It is clearly understood that many of the challenges facing ASM/ASGM, including environmental and public health in sub-Saharan countries, are due to economic instability (Mutagwaba *et al.*, 2018). The Government of Ecuador through its Mining Act Chapter V Art. 49 has developed a trading system that seems to support the ASGM subsector (Ecuador Government, 2015). Gold from the ASG-miners is marketed by the government through the Central Bank. Marketing can be done directly or indirectly through authorized financial institutions acting as intermediaries. This is different from many sub-Saharan African countries including Tanzania, where ASGM sells its Gold to individual brokers (Fig. 4), which reduces the price of gold. Furthermore, the issues of public health protection to workers and communities around the mining premises are clearly stipulated in Articles 58 and 68 of the Ecuadorian Mining Act (Ecuador Government, 2015).

The government of Tanzania has made efforts to support the mining sector. Efforts such as the building and operating mineral markets, the Melerani wall, providing areas for mining activities for the ASM/ASGM subsector, and other strengths as mentioned in Tables 2, 3, and 4 aim to improve the sector. However, there are some challenges that still face the ASM/ASGM. This might be due to little inclusion of the ASM/ASGM issues in many Tanzania regulatory frameworks that directly govern the sector. This was evidenced in the 27 official documents analyzed in this study, 84.6% (22 documents) their objectives and general statements did not touch the "ASM/ASGM" issues. This analysis showed that existing regulations would do little in solving or at least mitigating the problems facing the ASM/ASGM in Tanzania, making it difficult to achieve the SDGs and the Tanzania five years development plan 2021/22-2025/26 (URT, 2021). The SDGs call for meeting current needs while safeguarding the Earth's life support system, on which the welfare of current and future generations depends (David *et al.*, 2013). In addition, the Tanzania five-year development plan 2021/22-2025/26, among many targets and areas of interventions, emphasizes reducing environmental pollution and human health risk in the ASM/ASGM environment and protecting the environment from climate change (URT, 2021).

Given the challenges of ASGM in Tanzania, it is evident that no single policy, rule, regulation, act, guideline, or program will make it easy to solve ASGM-related problems. It is vital to have a better understanding of how Tanzania's mineral resource development sector can use ASGM to improve the economy while empowering people and protecting the environment and public health. It is believed that multi-stakeholder training initiatives and educational outreach aimed at both community members and miners would be a sensible first step toward empowering the community and paving the path for long-term changes to official government policies and sector-wide improvements (Ecuador Government, 2015; Kyaw *et al.*, 2021; Miserendino *et al.*, 2013). The challenges of ASM/ASGM, as detailed in Tables 2, 3, and 4, should be reconsidered, as a longer-term solution is needed. Therefore, revision of the laws, policies, strategies, and all other official documents governing the mining sector in Tanzania is strongly needed. This would make the mining and environmental legislation compatible with the ASM/ASGM reality.

2.7 Exposure Pathways and their Implications

An exposure pathway shows how radionuclides and trace elements migrate through their source to the final receiver, such as the human body. There are five components for an exposure pathway as pertains to ASGM (Pierzynski *et al.*, 2005). The first is the source of pollution in the environment. Tailings from gold mines are a main cause of pollution in the environment. Mine water can contaminate oxidized ore if it encounters it. Process water used in mining operations, such as washing soils in ASGM, is another cause of contamination. Process water frequently contains dissolved pollutants that, if released into the environment by seepage, evaporation, or runoff, could harm the environment and human health. In some cases, the water from the mining pits in the ASGM is used for household purposes (Focus *et al.*, 2021). Therefore, frequent ingestion and body contact of contaminated water can result to carcinogenic and/or non-carcinogenic health effects to the residents.

The environmental medium is the second route of exposure. A pollutant moves from its source through environmental media, such as wind, to sites where human and non-human exposure is possible. These sources of radionuclides and trace elements later percolate into underlying groundwater aquifers and discharges into surface water bodies through runoff causing pollution in water supplies. Soil, water, air and food are the key environmental media relevant to human health and environmental health (Pierzynski *et al.*, 2005). Through surface water, people may be exposed to trace elements and radionuclides. Drinking, bathing, farming and recreational uses are all possible exposure routes to surface water and groundwater. People may also be exposed to outdoor and indoor air polluted with ^{222}Rn gas and windblown dust from mine waste through atmospheric deposition. Human exposure can also be caused by eating foods irrigated with contaminated water or grown on contaminated land. Contaminated soil carried through the air as dust can settle on the surface or on food products, where it can be inhaled or swallowed (Kabata-Pendias & Mukherjee, 2007; Mohammed *et al.*, 2011).

The point of exposure is the third component of the human exposure pathway. This is the point where a contaminant comes into contact with a person (Kamunda, 2017). Radionuclides and trace elements, for example, can be found in dwellings, waterways, and workplace. The fourth component of the exposure pathway for trace and radioactive elements is the receptor. Workers, for example, could be more exposed if they work without protection in a polluted environment.

The route of exposure is the fifth factor. This is how a contaminant enters the human body. People can take radionuclides and trace elements into their bodies through three different mechanisms: ingestion, inhalation, and dermal contact (Focus *et al.*, 2021). Apart from ingestion, inhalation, and dermal contact exposure routes, direct external irradiation is another important source of exposure (Kamunda, 2017). This occurs when a person is exposed to ionizing radiation from the ground or air. Figure 2 shows several potential paths of exposure to radionuclides and trace elements, which can be viewed as a conceptual model for this study. It is noted from Fig. 2 that human beings can get health risk through different environmental media such as water, air, food, and soil. Because risk is additive, nature and behavior of people living and working in an area might accelerate the level of risk. For example, a person might be exposure thorough all the routes if he/she do not use protective equipment. It has also to be noted that in radiation protection three important things must be considered, these are shielding, distance, time, and duration of exposure.

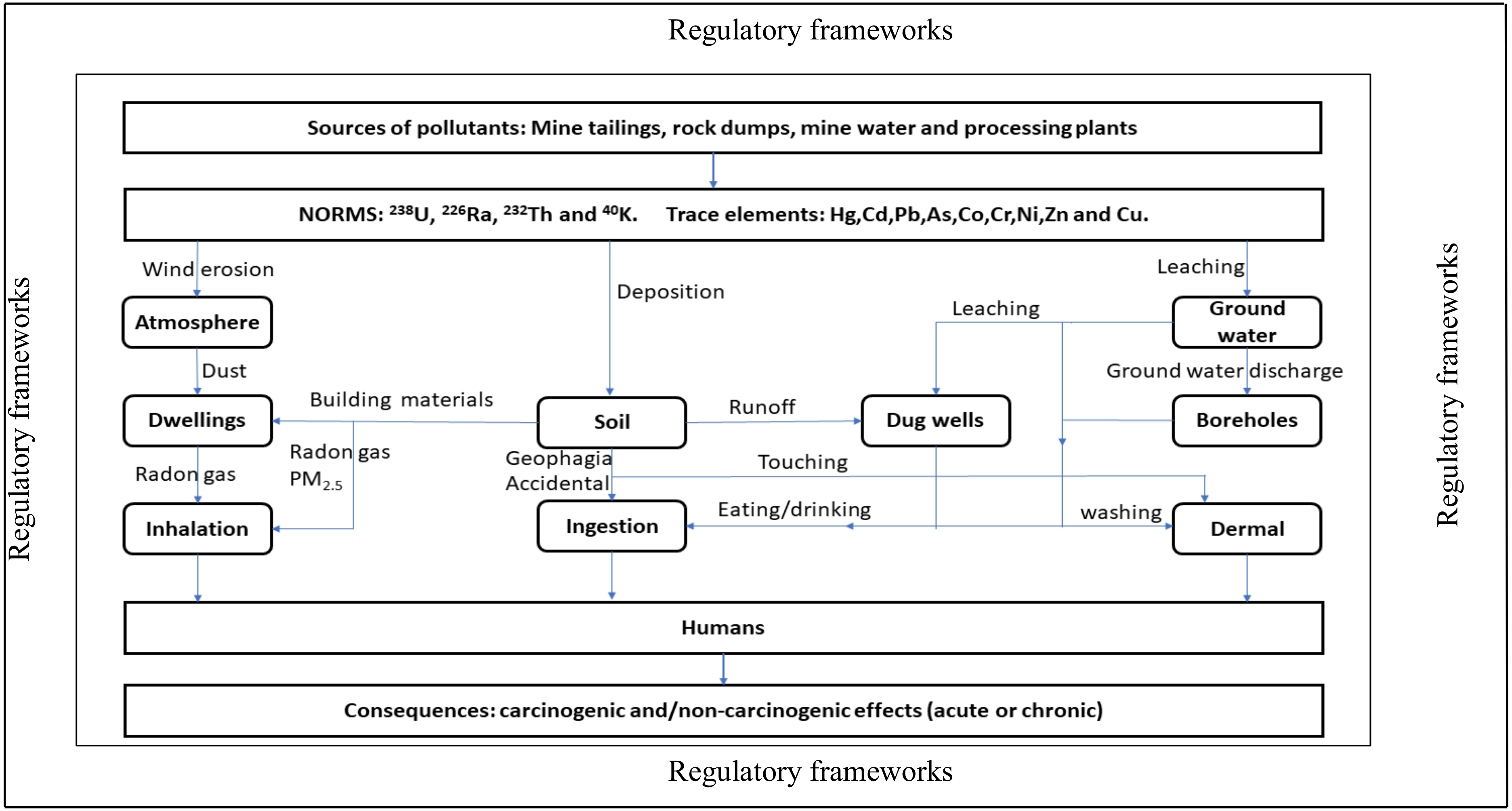


Figure 2: Source-Pathway-Receptor Approach: The Study Area's Conceptual Model

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the Study Area

This study was conducted in the Geita region of Tanzania. The Geita region lies on the Southwest bank of Lake Victoria. It occupies 20 052 km^2 with a population of about 1 739 530 people (URT, 2013), mostly occupied by the Sukuma ethnic group. The economic activities practiced in the region include small-holder farming (mostly paddy and maize) and livestock keeping. Recently, the ASGM activities has become a fast-growing sector in the region. Geologically, Geita is found in the gold-rich region, the Lake Victoria goldfields (LVGF). Many of Tanzania's LSGM operations as well as ASGM activities occur in these goldfields (Henckel *et al.,* 2016). The 2011/12 Census carried out by MEM showed that nearly 24% of all ASGM operate within the Geita region (MEM, 2016). Thus, the Geita region was purposely chosen because of its long history of mineral extraction of both ASGM and LSGM in the gold-rich country of East Africa. The ASGM in Geita is done in different sub-districts including Nyarugusu, Rwamagasa, Nyakagwe, Nyamtondo, Iparamasa, Nyamalimbe, Kamena and Mgusu. The present study was carried out in the Rwamagasa sub-district located at 3.11660 S and 32.04170 E with about 4000 ASGM miners (Fig. 3) (Kivyiro, 2017).

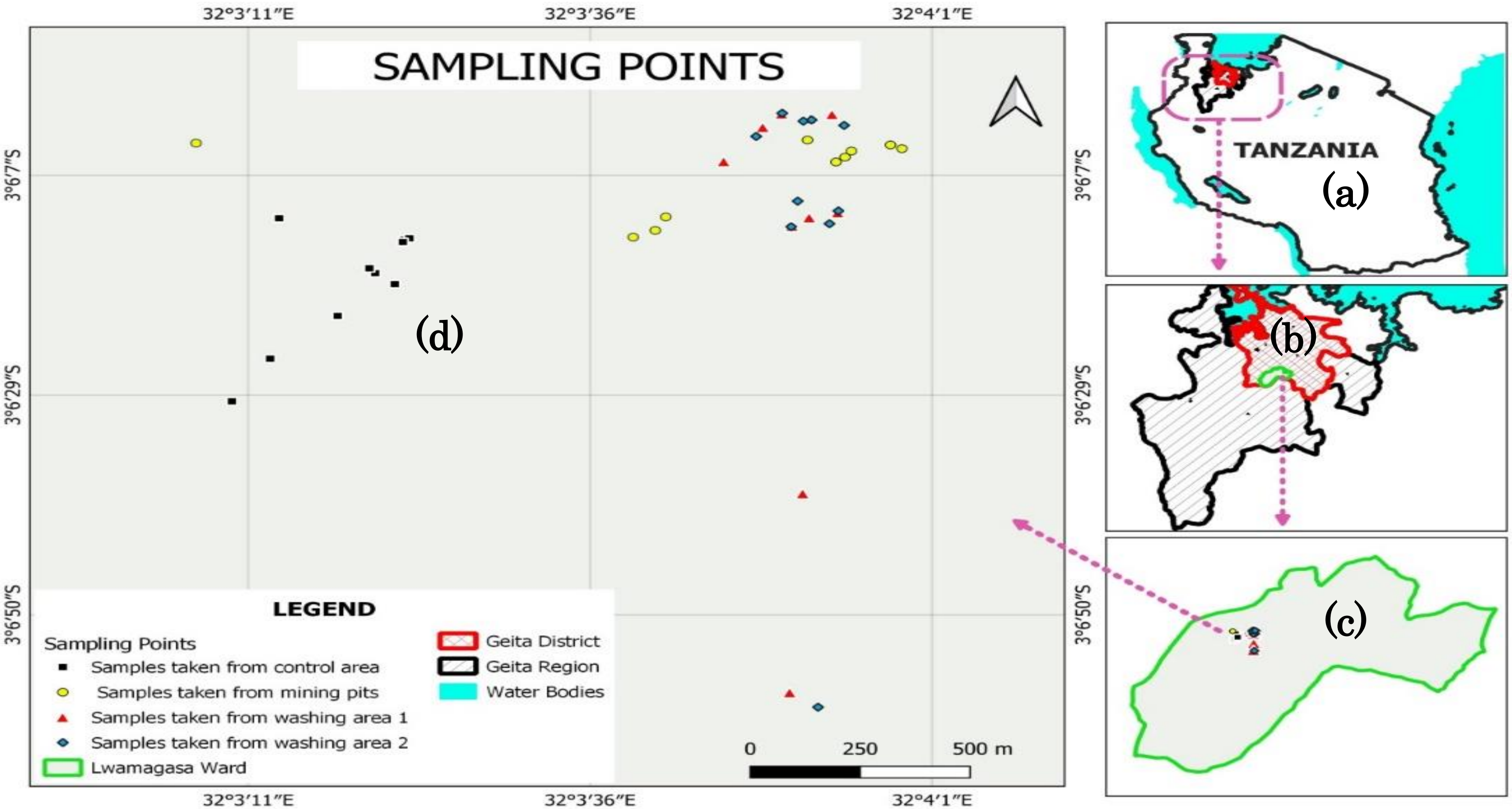


Figure 3: **(a) Map of Tanzania (top right) showing Geita district (b), and the bottom right shows sampling points (c) as enlarged at the left side (d)**

Rwamgasa has been a hub of ore processing for the nearby ASGM centers (Mutagwaba *et al.*, 2018). Many on-site brokers in Rwamgasa buy small gold collections and sell them to larger brokers in Dar es Salaam, Mwanza and Geita. The Katoro town, which is located on the highway that connects Mwanza to Rwanda, Uganda, Democratic Republic of the Congo and Burundi, has grown into a significant gold trading center, attracting miners from nearby ASGM centers. Figure 4 shows a typical ASGM theoretical model of operation of the study area.

At the study area (Fig. 4) the Primary Mining License (PML) owners have sufficient capital compared to the pit-owner and miners. Majority of the miners are paid a daily basis by estimating the value of mined materials. Pit owners on the other hand acted as supervisors to the respective mining pit (s). Also, brokers buy gold from the miners and pit-owners and sell them to other dealers. Figure 4 depicts these interactions indicating the main and rare trading routes.

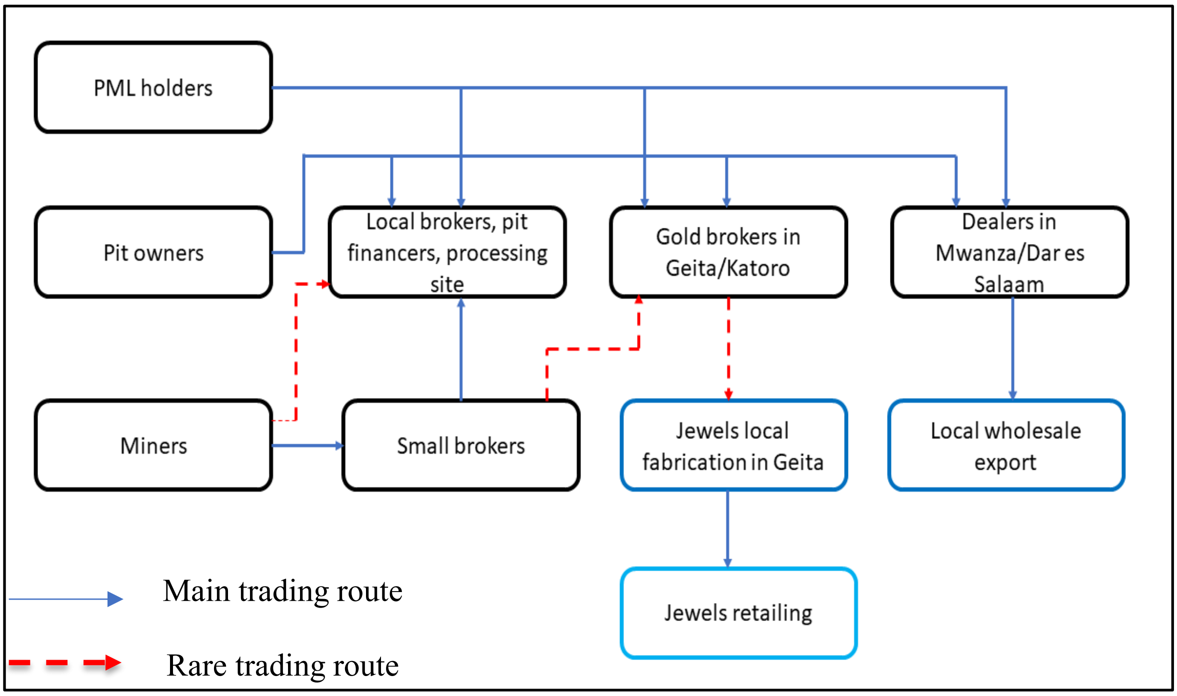


Figure 4: Typical ASGM theoretical model of operation in Rwamagasa which might represent other ASGMs in Tanzania

Various socio-economic activities that might endanger human health were found being conducted at Rwamagasa ASGM, including but not limited to: (a) the miners' families residing in the mining area, (b) small guest housing businesses, and (c) small-scale farming practices by resident community, such as gardening, crop cultivation, and animal keeping and poultry production. During a pre-study visit, residents reported that it was common for children to play with soils at the Rwamagasa ASGM, while expecting mothers and mothers with newborns were active in soil transfer, and washing the mined materials, albeit with little protection (researchers' observation). Observations from the pre-study visits also revealed that artisanal and small-scale miners in the study area worked long hours (for example some men were working more than 13 hours continuously in the mining pits) without protective gears. Despite the gravity of the problem, research on trace and radioactive element exposure and related health concerns to miners and communities is lacking, not only in Tanzania but across sub-Saharan Africa. Therefore, the goal of this study was to investigate the levels of different trace and radioactive elements in soils and water obtained from a typical ASGM and analyze the health risk to residents and mine workers.

3.1.1 Sampling Areas

The detailed characteristics of sampled areas and points indicating codes and descriptions of the study sites are shown in Table 5.

Table 5: Sample Codes and Descriptions

Code	Descriptions
MD	Soil samples taken from the mining pits for trace element analysis. Some mining pits were located near residents about 20 meters, the pits are fenced by the huts. However, soils dug from the pits are scattered even outside the huts. The hips of soil in these areas are characterized by high dust because it is not wetted.
WA	Soil samples for trace element analysis taken from the first washing area. In the first washing area, the grinded mined materials are washed for the first time to reduce dust concentration. These areas are located a bit far (about 100 meters) from the residences.
WB	Soil samples for trace element analysis taken from the second washing area. In the second washing area, the washed materials in WA are re-washed to identify gold segments. This activity is done adjacent to WA.
C	Soil samples for trace element analysis taken from the control area. The control area was about 4 km from the mining site, the area had scattered residences practicing small-scale farming.
MP	For water and soil samples taken from the mining pits for radioactivity analysis; the water from the mining pits is occasionally used for domestic purposes. Some mining pits were located near residents about 20 meters, the pits are fenced by the huts. However, soils dug from the pits are scattered even outside the huts. The hips of soil in these areas are characterized by high dust because it is not wetted.
W1	Soil and water samples for radioactivity analysis taken from the first washing area. Water used in W1 was taken from the mining pits. After settling this water was used for hands, legs, and even faces washing.
W2	Soil and water samples for radioactivity analysis taken from the second washing area. Water used in W1 was taken from the mining pits. After settling this water was used for hands, legs, and even faces washing.
CTR	Soil and water samples for radioactivity analysis taken from the control area. Water was taken from the boreholes which are used by residents for domestic uses.
CD	Will refer radon measurements taken from the control dwellings, these houses had similar characteristics as those from the mining area but situated about 4 km from the mining area.
D	This refers to radon samples taken from houses found in the mining area. The main construction material for these houses is soil and bricks made of soil. These houses are also characterized by poor ventilation and majority are built close to the mining pits.

3.2 Soil Trace Elements

3.2.1 Soil Sample Collection

A total of 74 soil samples were collected from the study area. Sampling points were grouped into four categories: WA referring to 18 soil samples taken from the first washing area, WB referring to 17 soil samples taken from the second washing area, MD referring to 29 soil samples taken from the mining pits and C referring to 10 soil samples taken from a control area. At each sampling area, a sample was taken from three different points and then mixed to represent the entire area.

All representative soil samples were placed in labeled polythene bags and transported to the Nelson Mandela African Institution of Science and Technology (NM-AIST) for preparation and storage, and later were transferred to the Tanzania Atomic Energy Commission (TAEC) laboratory for analysis. For future referencing purposes, all sampling points were geo-referenced using a handheld GPS receiver.

3.2.2 Sample Preparation

Soil samples were dried in an oven at a temperature of 50°C for 24 hours to remove moisture and obtain constant weight (Carter & Gregorich, 2007). The soil samples were then crushed into a fine powder using a thoroughly cleaned mortar and pestle using acetone to obtain particle sizes passing through a 2 mm stainless steel sieve. Thereafter, 4 g of a sieved soil sample and 0.9 g of the starch binder were measured and mixed. A mixture of binder and sample was homogenized using a pulverizer (serial number 1336, Fritsch GmbH, Germany) for ten minutes and then pressed into 32 mm diameter tablets with a die pellet maker (PP25, serial number 1261603100, Retsch GmbH, Haan-Germany).

3.2.3 Laboratory Measurements and Analysis

Soil samples were measured and analyzed for trace elements using the Energy Dispersive X-ray Florescence (ED-XRF; XOPOS, 4R0138, Kleve, Germany). The spectrometer was calibrated before ED-XRF analysis was performed. The pellet samples were put into the ED-XRF, where the elemental compositions and concentrations were determined. The ED-XRF method has the advantage of high sensitivity, nondestructive and specificity for the correct detection and quantification of trace elements (Kamunda *et al.*, 2016). The accuracy of the analytical data was assured by employing the typical quality assurance procedures (Kamunda *et al.*, 2016). Each sample was analyzed in triplicate and an average was calculated to obtain the reported value. After each measurement of a category sample, a certified soil standard (Montana Soil 2711A) was run to check for contamination (Kamunda *et al.*, 2016). Trace element concentrations from the ED-XRF analysis were obtained in mg/kg and %; those obtained in percentages were converted into mg/kg for uniformity.

3.2.4 Health Risk Assessments

Experimental data obtained by measurements were employed in mathematical models 1 to 6 to estimate the health risk associated with the field conditions. The risk associated with ingestion of trace elements through soil ($ADI_{Ingestion}$) was estimated using Equation 1. While the health risk associated with inhalation of trace elements through soil ($ADI_{Inhalation}$) particulates was estimated using Equation 2. Equation 3 was used to evaluate the risk due to dermal contact with the soil (ADI_{Derm}). The carcinogenic and non-carcinogenic risk was assessed using Equations 4 and 5 for non-carcinogenic effects and Equation 6 for carcinogenic effects, respectively (Salmani-Ghabeshi *et al.*, 2016).

$$ADI_{Ingestion} = C \times RI \times f \times ED \times {}^{F}/_{B} \times T \tag{1}$$

$$ADI_{Inhalation} = C \times IR \times f \times {}^{ED}/_{B} \times T \times PEf \tag{2}$$

$$ADI_{Derm} = C \times ESA \times FES \times SAF \times ABS \times f \times ED \times {}^{F}/_{B} \times T \tag{3}$$

$$HQ = {}^{ADI_{Route}}/_{RD} \tag{4}$$

$$HI = \sum_{i=1}^{n} HQ_i = \sum_{i=1}^{n} {}^{ADI_i}/_{RD_i} \tag{5}$$

$$Risk_{pathway} = \sum_{i=1}^{n} ADI_i \, CSF_i \tag{6}$$

where *C* is the concentration of trace elements in soil, *RI* is the ingestion rate, *f* is the exposure frequency, *F* is the conversion factor, *B* is the body weight, *T* is the period over which the dose is averaged, *ED* is the exposure duration, *PEf* is the particulate emission factor, *ESA* is the exposed skin area, *FES* is the fraction of dermal exposure ratio to soil, *SAF* is the soil adherence factor, *ABS* is the fraction of the applied dose absorbed across the skin, *RD* is the reference dose of a specific chemical and *CSF* is the cancer slope factor. The exposure parameters used in this study are presented in Table 6.

Table 6: Exposure parameters for children and adult population used in the present study

Parameter	Unit	Adult (17^{+} years)	Child (1-16 years)
Ingestion rate	mg/day	100	200
Exposure duration (*ED*)	years	30	6
Body weight	kg	70	15
Inhalation rate	m^3/day	20	10
Exposure frequency	days/year	350	350
Dermal exposure ratio	—	0.61	0.61
Conversion factor	kg/mg	10^{-6}	10^{-6}
Dermal absorption factor	—	0.1	0.1
Skin surface area	cm^2	5800	2100
Soil adherence factor	mg/cm^2	0.07	0.2
Average time			
For carcinogenic	days	365 × 70	365 × 70
For non-carcinogenic		365 × *ED*	365 × *ED*

Bakshi *et al.* (2018)

*+ = and above

Additionally, the cancer slope factor and the reference doses for different trace elements are presented in Table 7 (Warren-Hicks *et al.*, 1989).

Table 7: Reference doses (mg/kg-day) and cancer slope factor for different pathways used in the present study

Trace element	Oral *RD*	Dermal *RD*	Inhalation *RD*	Oral *CSF*	Dermal *CSF*	Inhalation *CSF*
	x 10^{-4}					
Cr	30	NA	0.3	0.5	NA	4.1
Cu	370	240	NA	NA	NA	NA
As	3	3	3	1.5	1.5	15
Hg	3	3	0.86	NA	NA	NA
Pb	36	NA	NA	0.005	NA	0.042
Cd	5	5	0.57	NA	NA	6.30
Zn	3000	750	NA	NA	NA	NA
Ni	200	56	NA	NA	NA	NA
Co	200	0.057	0.057	NA	NA	9.80

Warren-Hicks *et al.* (1989)

*NA = Not indicated

3.3 Soil and Water Radioactivity

3.4.1 Sample Collection and Preparation

Samples for the radioactivity were labeled differently from those for trace elements. In this section, note that MP will represent samples from the mining pits, W1 will mean samples from the first washing area, W2 will stand for samples from the second washing area and CTR will refer samples taken from the control area (Table 5). In this part, 40 samples were investigated for soil radioactivity. Ten (10) soil samples were taken from MP, another 10 soil samples were taken from W1. In W1, the soil is washed for the first time after being crashed with crashing machines (or using hands (Appendix 8 (16)) characterized by high dust concentration. Also, 10 soil samples were taken from W2. In W2 the soil from WA was re-washed to identify soil which might contain gold. Ten (10) soil samples were taken from the CTR area about 4 km from the mined area.

Soil samples were firstly ruptured into reduced aggregates, followed by a thorough drying at a temperature of 50 °C in a drying cabinet to hasten the drying process (Avwiri *et al.*, 2013). The dry soil samples were then crashed using a mortar and pestle, sieved through a steel 2 mm sieve, packed in sealed canisters, and kept for no less than 28 days to attain secular equilibrium needed for gamma ray spectrometry analysis (Habib *et al.*, 2018).

Water samples were collected from four different areas: CTR (5 samples), an area of about 4 km from the mining sites, 10 samples each from MP, W1, and W2. The water from the MPs was occasionally used for domestic purposes, and the water from W1 and W2 when settled was used by miners and soil washers for hand washing. Also, this water was used for agricultural activities. In addition, the CTR water samples were the groundwater collected from boreholes offsite used by the residents for agricultural and domestic purposes.

Water samples were collected in one-liter transparent plastic bottles that were thoroughly rinsed with distilled water before being transported to the study area. Prior to sample collection, the pre-cleaned sampling bottles and bailer were completely rinsed with water from the sampling source to ensure that the samples were kept free of cross-contamination. A one-liter sample was taken in a plastic bottle at each sampling location. To inhibit bacterial activity and radionuclide adsorption on the sample container walls, samples were acidified to $pH < 2$ with 2 mL nitric acid. With the assumption that radionuclides were dissolved and not in a particle fraction, the pre-treated samples were filtered (0.45µm) to eliminate particulates (Banzi *et al.*, 2016; Knoll, 2010). Before being stored in a cooler at a temperature of about 4°C, the filtrates were packed separately in polyethylene bottles, sealed, and labeled with the sampling date and code. Each sampling point was geo-referenced using a GPS and recorded in a prepared field data sheet. The samples were taken to the laboratory at the Tanzania Atomic Energy Commission (TAEC). In the laboratory, samples were filled in a 500 cm^3 clean Marinelli beaker, sealed, and left for at least 28 days for secular equilibrium before analysis.

3.4.2 Radioactivity Analysis

Soil samples were analyzed using a lead-shielded coaxial high-purity germanium detector (HPGe, serial number 57-P51572A, ORTEC, USA). The detector cavity was sheltered with three liners of Pb, Cd and Cu of 100 mm, 3 mm and 30 mm thick, respectively to prevent background radiation in the counting surroundings. The system has a relative efficiency of about 51% and a resolution at Full-Width Half Maximum (FWHM) of about 7.2% at the energy of 0.662 MeV (^{137}Cs), which is adequate to resolve the gamma-ray energies of interest. The gamma-ray energy calibration was conducted every day using multi-nuclide sources of ^{137}Cs, ^{133}Ba, ^{57}Co, ^{109}Cd, ^{60}Co, ^{22}Na and ^{54}Mn. The efficiency standardization was performed using in-situ object counting system of Genie 2000 software (Fatima *et al.*, 2007). The activity concentrations of the radionuclides in the samples were determined from corresponding gamma-ray lines emanating from the decay products. The gamma line of 1460.8 keV was used to determine ^{40}K. The weighted mean activity levels from gamma lines of 583.1 keV (^{212}Pb), 2614.5 keV of ^{208}Tl and 911.1 keV (^{228}Ac) were used to determine ^{232}Th. The gamma lines of 609.3 keV (^{214}Bi), 1764 KeV of ^{214}Bi, 295.2 keV (^{214}Pb), and 186.1 keV (^{226}Ra) were used to determine ^{226}Ra.

The International Atomic Energy Agency (IAEA) Soil number 375 was used as a standard reference material to assess the accuracy and precision of the results. The standard was counted for the similar geometry as used for the samples, its activity at different energies were determined and equated with the certified value after correction of the decay based on the date of December 31st, 1991, provided in the data sheet. The experimental concentration values were in line with the suggested values within 10% accuracy (Table 8).

Table 8: The experimental activity values (Bq/kg) and the standard reference values

Radionuclide	Energy (keV)	Certified reference value	Experimental activity concentration	Accuracy (%)
^{226}Ra	186.1	20.0±0.9	20.53±0.6	3.0
^{40}K	1460.8	423.40±0.2	499.89±2.2	0.4
^{214}Pb	295.2	19.96±0.8	19.54±0.7	3.6
	351.92	19.96±0.5	21.01±1.2	5.7
^{214}Bi	1764	19.96±0.4	19.98±0.9	4.5
	2477.7	19.96±0.9	20.34±1.3	6.4
^{208}TI	860.4	20.46±0.3	21.19±1.0	4.7
	2614.5	20.46±0.6	22.44±1.8	8.0
^{228}Ac	338.5	20.46±0.3	20.52±1.6	7.8
	911	20.46±0.5	21.32±0.8	3.7
	968.5	20.46±0.5	22.69±1.1	4.8

The calibration of high-resolution gamma spectrometers in water samples allows estimation of radionuclide in the samples. The certified Reference Materials (CRM), IAEA-423 and IAEA-426, were used to validate the energy and efficiency calibration. All the samples including the standard sample were tallied in the system using a counting time of 24 hours.

In all the measurements, quality control and quality assurance procedures were performed to check for instrument performance and accuracy of measurements. These included regular background and calibration source measurements. The gamma photons from the samples were detected by placing the canister or Marinelli beaker directly over the HPGe detector. Each soil sample was counted for 10 hours to allow for measurable activity. To allow for detectable activity, each water sample was counted for 24 hours. The background radiation inside the shielding was also measured using an empty canister or Marinelli beaker for soil and water samples, respectively. The activity concentration of each sample was obtained by subtracted the count rates of background from the total count rates of the sample and background. Since detection efficiencies for gamma rays vary with energy, their determination for specific radionuclide energies was done during the calibration process. The counting geometry was created during efficiency calibration and carefully repeated for all the radionuclides.

3.4.3 Activity Determination

The activity concentrations of the samples were determined using the net area under the photo peaks using Equation (7).

$$A = \frac{N_c}{\gamma_p \times T \times \eta(E) \times m_s} \quad (7)$$

where A is the activity concentration of the radionuclide in the sample in Bq/kg, m_s is the mass of the sample in kg, η *(E)* is the detector efficiency at the specific γ-ray energy, T is the counting time, γ_p is the absolute transition probability of the specific γ-ray, and N_c is the net count rate under the corresponding peak.

3.4.4 Public Exposure Dose from Gamma Rays

The mean dose rates absorbed in the air from gamma emission were estimated using Equation 8 (UNSCEAR, 1993). The calculation was based only on ^{226}Ra, ^{232}Th, and ^{40}K assuming that concentrations of other elements such as ^{90}Sr, ^{137}Cs and the decay series of ^{235}U can be neglected due to insignificant concentration contributions to the whole environmental background doses (Kocher & Sjoreen, 1985). This dose gave the information on the exposure due to emissions and not the amount received in the human body.

$$D = 0.043A_k + 0.662A_{Th} + 0.427A_{Ra} \quad (8)$$

where D is the dose rate (nGy/h) at 1m above the ground due to ^{226}Ra, ^{232}Th and ^{40}K in the soil samples, A_K, A_{Th} and A_{Ra} are the activity levels of ^{40}K, ^{232}Th and ^{226}Ra in Bq/kg, respectively.

The dose conversion coefficient (0.7 Sv/Gy) was used in the estimation of the annual effective dose due to the natural radionuclides. The occupancy of 0.2 for outdoor (average of 4.8 hours spent outdoor every day in a year) as suggested by UNSCEAR (UNSCEAR, 2020) was used. The effective dose rate was estimated using Equation 9 (Jibiri & Adewuyi, 2008). This dose indicated the amount of radiation that normally affects the human body negatively.

$$E_{eff} = T * O_f * Q * D * X \quad (9)$$

where E_{eff} is the effective dose rate in mSv/y, T is the time in seconds in a year, O_f is the occupancy term which fixes the mean time spent outside in the area, Q is the proportion of the effective and absorbed dose rate in air, X is the factor converting units to the micro from nano scales and D is the absorbed dose rate in air in nGy/h.

3.4.5 Radium Equivalent Dose

For the assessment of the associated risk due to gamma radiation exposure to people linked with interactions with soil from the mining site, radium equivalent level was estimated. This provided a particular index which defined the gamma yield from a diverse mixture of ^{226}Ra, ^{232}Th and ^{40}K in the samples. Radium equivalent activity (Ra_{eq}) is given by Equation 10 (Isinkaye *et al.*, 2018).

$$Ra_{eq} = 0.077A_k + 1.43T_h + A_{Ra} \quad (10)$$

where A_K, A_{Th} and A_{Ra}, are the activity concentration of ^{40}K, ^{232}Th and ^{226}Ra, respectively.

3.4.6 The Internal Hazard Index

For the determination of the internal hazards due to soil which when accidentally ingested, Equation (11) (UNSCEAR, 2020) was used.

$$H_{in} = \frac{C_k}{4810} + \frac{C_{Th}}{259} + \frac{C_{Ra}}{185} \leq 1 \quad (11)$$

Where: H_{in} is the internal hazard index and C_K, C_{Th} and C_{Ra} are the activity concentration of ^{40}K, ^{232}Th and ^{226}Ra, respectively.

3.4.7 The External Hazard Index

The hazard due to the natural gamma radiations contacted externally by the human body was estimated using Equation 12 (UNSCEAR, 2020). For the safety purpose, this value must be kept less than unity.

$$H_{ext} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_k}{4810} \leq 1 \quad (12)$$

where: A_{Ra}, A_{Th} and A_K are radioactivity concentrations (Bq/kg) of radium, thorium, and potassium, respectively from the sample.

3.4.8 Representative Gamma Index

Equation 13 was used to derive the gamma activity value index (*Iγ*) for pinpointing if soil is safe for building materials such as bricks (Ademola & Obed, 2012; Avwiri & Agbalagba, 2007). A value less than unity is considered to be safe.

$$I_\gamma = \frac{A_k}{1500} + \frac{A_{Th}}{100} + \frac{A_{Ra}}{150} \tag{13}$$

3.4.9 Annual Gonadal Equivalent Dose

Referring to (UNSCEAR, 2020), the gonads, the bone surface cells and the active bone marrow are reflected as the organs of attention in radiation protection. Thus the annual gonadal equivalent dose ($AGED$ mSv/y) for the residents of Rwamagasa due to the specific activities of ^{40}K, ^{226}Ra and ^{232}Th was estimated using Equation (14) (Arafa, 2004).

$$AGED = 0.314A_K + 3.09A_{Ra} + 4.18A_{Th} \tag{14}$$

where A_K, A_{Ra} and A_{Th} are the activity concentration of ^{40}K, ^{226}Ra and ^{232}Th, respectively

3.4.10 Alpha Index (Iα)

This index is necessary to calculate alpha radiation contact resulted from inhalation of radiation from building materials such as soil. This index was estimated using equation 15 (Tufail *et al.*, 2007).

$$I_\alpha = \frac{A_{Ra}}{200} \tag{15}$$

where as A_{Ra} is the ^{226}Ra activity concentration (Bq /kg) in the soil.

3.4.11 Annual Dose Equivalent for Water Ingestion

The annual effective dose (E_I) for members of the public from ingestion of ^{238}U, ^{232}Th and ^{40}K through water samples is calculated using the activity concentrations of each radionuclide observed in the sample. Equation (16) was used in the calculation (UNSCEAR, 2020):

$$E_I\left({}^{mSv}/_{y}\right) = \sum_{I=1}^{3} A_{rd} IR_I EDC_I \tag{16}$$

where A_{rd} is the activity concentration of radionuclides in a sample, IR_I denotes the annual water consumption rate, and *EDCI* denotes the effective dose coefficient in Sv/Bq for natural radionuclide ingestion. For ^{238}U, a value of 4.50×10^{-8} was used. A value of 2.30×10^{-7} was used for ^{232}Th, and 6.20×10^{-9} was used for ^{40}K (ICRP, 2019). The yearly effective doses for water samples were calculated using an annual water consumption rate of 600 Litres/year for people (Fristachi & Rice, 2007).

3.4 Radon-222 Measurements

The radon levels were measured in MPs and dwellings (Ds) from 25 sampling areas. Ten (10) measurements each were taken from the MPs and Ds situated within the mining area. Five measurements were taken from the control houses (CDs) (about 4 km from the mine). From each sampling point, radon detection device (Alpha, 1998) was set to measure the radon level in every ten minutes cycle for six hours. The instrument was placed at least 1 meter from any obstacle to allow easy air flow into the device. The hourly and overall means were recorded. The intake (I) and annual absorbed dose (D) due to radon gas were estimated using Equations 17 and 18, respectively.

$$I = C_{Rn}\left({}^{Bq}/_{m^3}\right) \times F \times P(h) \times R\left({}^{m^3}/_{h}\right) \tag{17}$$

$$D(msv/y) = C_{Rn} \times D \times P(h) \times F \times T\ (h) \tag{18}$$

where, I, C_{rn}, F, R, P, T and D, are the Intake, Radon concentration, Equilibrium factor, Breathing rate, Occupancy factor, Occupancy time and Dose conversion factor, respectively.

Statistically, the control points for soil, water, and radon gas were established basing on the spatial distribution of concentrations from the active mine. For the soil radioactivity, walkover gamma radiation survey was conducted using hand-held instruments to establish background levels. This survey was conducted on the entire area downwind in accordance with dose rates measurements as described elsewhere (US Nuclear Regulatory Commission, 1992). From the active mining area, a constant reading averaged 0.9 nSv/h compared to an average value of 8 nSv/h recorded within the active mining area was recorded at about 4 km. The geological characteristics of the control area was like that of the mining area. Water radioactivity and indoor radon gas followed similar procedures as that for soil. For soil trace elements, a pilot study considered samples taken from two layers; a top layer and at a depth of about 30 cm. Samples were drawn at every 500 m downwind from the active mine. The preliminary laboratory analysis revealed a constant level at about 4 km from the mining area. This area had similar geological features as the active mine hence taken as the control area.

3.5 Policy Analysis

For objective three, this work used content analysis of several official documents. Relational analysis was used to develop the conceptual analysis further by examining the relationships among concepts in a text (Downe-Wamboldt, 1992). A total of 27 documents related to mineral and mining sector of Tanzania have been analysed. These documents include: six (6) policies, 12 acts/laws, 5 regulations and 4 strategies. Also, official documents from other countries such as Ghana, Namibia, and Australia (African Union, 2013; Ayee *et al.*, 2011; Dwiki, 2018; Hepburn, 2015; Wilcox, 2015) were reviewed. Journal articles, reports, books, thesis, and dissertations were referred. These documents were filtered from google search engines from different platforms such as google scholar and ResearchGate. Figure 5 shows the summary of steps followed in relational analysis.

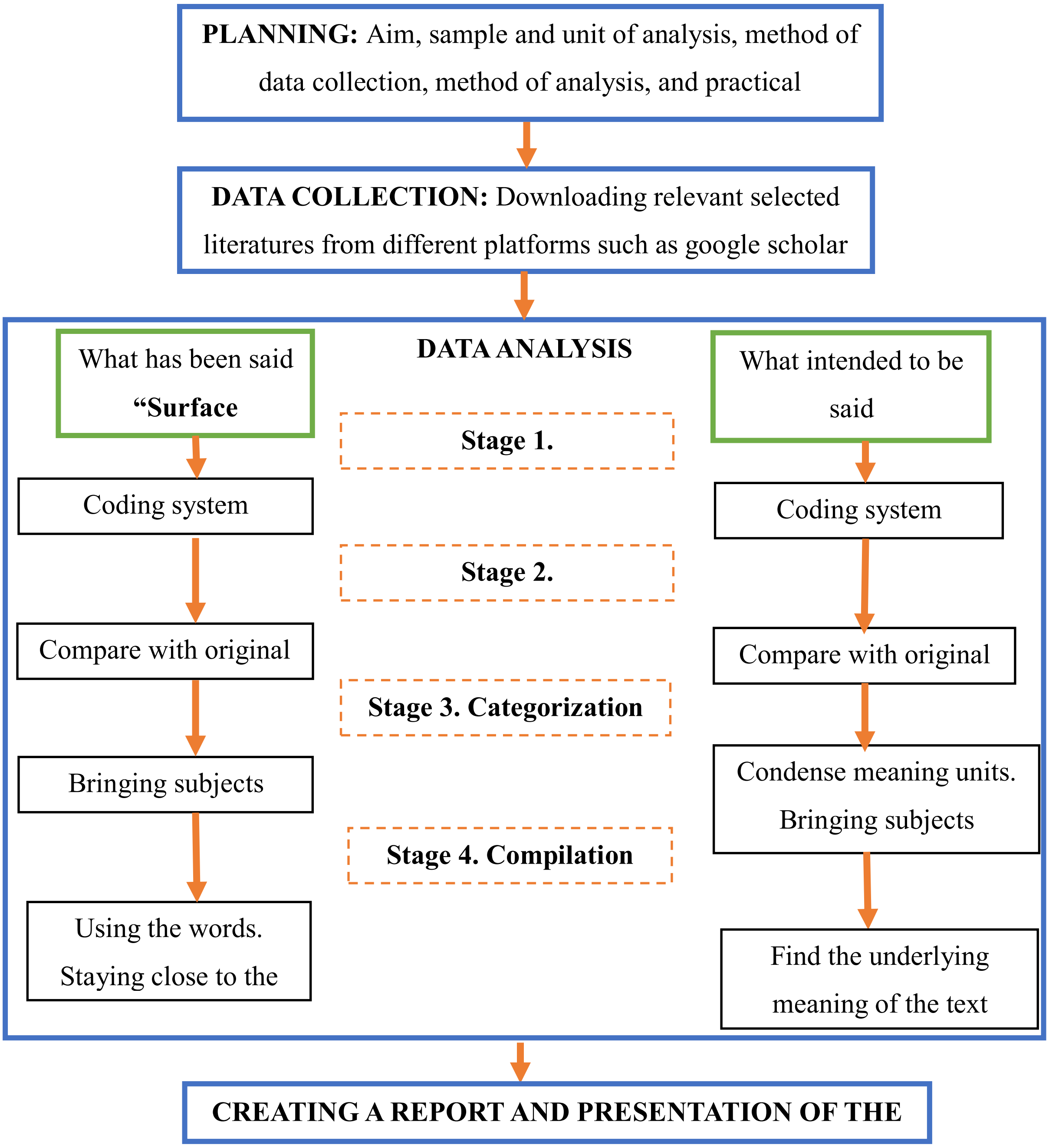


Figure 5: Processes of a content analysis method used in regulatory framework analysis

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This Chapter presents the results and discussions on trace elements (Cr, Co, Ni, Cu, Zn, As, Cd, Hg, and Pb) in soil. The radiological hazards for carcinogenic and non-carcinogenic effects of the selected trace elements are also presented and discussed. Levels and health risk assessment of selected natural radionuclides (^{238}U, ^{232}Th and ^{40}K) in soil and water are also presented. The results obtained from the inhalation of radon from dwellings and Mining Pits (MPs) and the corresponding health risk indices are also presented. The Tanzania mineral and mining policymaking and regulatory framework with a ASGM perspective were also analyzed and discussed.

4.2 Field Observations

The Rwamagasa ASGM houses were found to have small rooms with inadequate ventilation. Field observations revealed that most of the houses had rooms with approximated dimensions of 2.5 × 2 × 2.5 (12.5 m^3) (Length (L) × Width (W) × Heigh (H)) (Fig. 6). It was also revealed that such a room could be occupied by two to four people. Many of the dwellings had small windows. The dimensions of windows generally ranged from 0.3 × 0.5 to 0.7 × 0.9 (L × W) m (Fig. 6).

Figure 6: A typical house found in the study area showing the ventilation structures

Additionally, some houses were built approximately 20 meters from the mining pits (Fig. 7). The building materials in and around the study area were mainly soils.

Figure 7: Various activities taking place at one of the study sites

The mining pits at the study area had all the characteristics of having high concentrations of radionuclides and radon gas. Field observations noted that the pits had inadequate ventilation, and their volumes were not large enough to allow good air circulation (Fig. 8 and 9).

Figure 8: A miner going down a mining pit

It was estimated that the depth of the mining pits ranged from 60 to 200 m, the pits diameters ranged from 0.9 to 1.4 m for the circular pits and for non-circular pits the dimensions ranged from 0.5 × 0.7 to 0.6 × 0.9 (L × W) m. Also, the miners at the study area spent long time in the pits during material excavation. This could have implications related to the prolonged contaminated air inhalation.

Figure 9: Indicating a miner descending into a pit using a rope

Generally, the study area had different characteristics from mine workers, pit structures, crushing and washing areas. Some pits were round (Fig. 8) while others had a square view (Fig. 9). Different workers were seen to have different protection at work. Some workers could be found with some protective gears such as safety boots, reflectors, and helmets. Whereas majority were working without any protection.

4.3 Soil Trace Elements

4.3.1 Trace Element Concentrations in Mining Pits (Sampling Site for Soil Trace Elements Samples [MDs])

The results in Table 9 show that the lowest level of Cu (51.86 ± 2.86 mg/kg) was recorded at MD13 and a maximum level of 737.66 ± 1.30 mg/kg at MD8. Arsenic was not detected at MD8 while the maximum level of As of 36.11 ± 1.29 mg/kg was recorded at MD26. On the other hand, Ni was detected with minimum and maximum levels of 44.65 ± 4.77 mg/kg and 131.61 ± 2.75 mg/kg at MD13 and MD29, respectively. Both Cu and Ni revealed minimum values of approximately equal magnitude at MD13. This phenomenon may indicate that at MD13, Cu and Ni were geologically found in trace amounts.

Table 9: Trace Element Concentrations in the MDs Sampling Points at Rwamagasa ASGM

Site ID	Location coordinate	Mean elemental concentration (mg/kg)								
		Cr	Co	Ni	Cu	Zn	As	Cd	Hg	Pb
MD1	S03º06.067’ E032º04.016′	60.31±2.99	19.24±2.73	94.74±3.61	196.43±3.24	148.82±3.72	6.77±2.78	6.05±2.78	0	6.67±2.31
MD2	S03º06.075’ E032º04.000’	59.69±1.29	12.48±4.55	100.89±3.81	134.84±1.10	146.91±1.78	10.74±3.32	2.01±0.21	0.07	18.32±1.53
MD3	S03º06.071’ E032º03.988’	46.12±6.68	24.60±1.68	118.31±4.82	182.46±4.20	148.87±1.10	13.46±3.02	10.30±0.02	0	9.68±1.40
MD4	S03º06.076′ E032º03.983′	41.76±5.13	18.55±3.19	86.37±4.85	237.46±3.30	151.31±1.04	10.89±2.09	5.21±2.02	0	4.19±0.46
MD5	S03º06.070′ E032º03.969’	113.23±4.34	14.07±3.82	78.32±2.91	150.10±3.10	87.78±1.81	14.63±3.45	0.03±0.01	0	15.08±0.54
MD6	S03º06.069’ E032º03.959’	53.58±2.03	14.17±2.42	95.36±1.25	214.26±0.87	133.43±3.48	10.74±2.89	3.13±2.43	0.09	5.40±0.97
MD7	S03º06.062’ E032º03.952’	86.86±3.41	11.66±2.27	84.33±4.97	118.37±1.15	108.83±0.76	14.03±3.08	4.78±1.23	0	7.95±1.21
MD8	S03º06.062’ E032º03.867’	53.87±10.38	27.21±2.76	89.03±4.39	737.66±1.30	150.16±2.63	0	7.14±2.95	0	15.74±0.86
MD9	S03º06.070’ E032º03.949’	55.13±7.56	13.83±3.49	97.88±3.23	152.64±6.47	133.78±1.66	8.73±1.98	7.86±3.10	0	4.58±0.49
MD10	S03º06.081’ E032º03.934’	51.85±0.75	20.37±1.28	128.40±4.06	178.36±5.39	154.25±5.59	25.9±4.89	10.45±0.77	0	7.66±0.59
MD11	S03º06.081’ E032º03.934’	45.29±4.17	18.90±5.11	89.97±9.00	172.07±2.41	165.46±1.91	5.48±0.08	6.32±00	0	3.04±1.11
MD12	S03º06.080’ E032º03.921’	63.31±4.76	10.63±2.27	67.88±3.22	133.27±2.81	126.98±0.94	17.73±4.87	6.09±2.21	0	4.58±0.74
MD13	S03º06.085’ E032º03.913’	46.91±2.74	10.68±0.86	44.65±4.77	51.86±2.86	126.04±1.89	5.94±0.96	5.32±1.23	0	4.09±0.13
MD14	S03º06.090’ E032º03.913’	40.23±1.67	12.10±2.57	87.13±2.27	167.87±4.26	126.98±1.68	18.79±5.12	7.60±0.01	0	4.35±0.15
MD15	S03º06.098’ E032º03.902’	75.35±0.23	19.63±2.82	97.98±6.71	155.85±3.05	108.65±0.13	8.09±3.36	9.21±0.81	0	3.34±0.61
MD16	S03º06.187’ E032º03.716’	41.95±6.14	22.59±2.60	138.39±3.84	170.06±4.68	149.49±3.67	22.8±4.32	9.01±0.00	0	4.32±0.61
MD17	S03º06.185’ E032º03.707’	34.45±2.09	20.72±5.61	88.55±1.67	184.34±1.94	157.28±2.00	3.89±0.09	13.98±2.42	0	4.32±2.25
MD18	S03º06.184’ E032º03.706’	52.32±4.66	24.21±5.99	98.43±2.59	149.19±1.52	172.14±1.74	6.99±1.43	6.36±2.07	0	7.33±0.72
MD19	S03º06.188’ E032º03.698’	47.31±0.62	19.14±1.52	122.25±6.00	108.09±3.07	142.68±4.03	9.53±1.23	7.31±2.10	0.06	3.14±0.87
MD20	S03º06.184’ E032º03.695’	41.63±5.98	17.57±1.56	108.46±4.61	167.97±3.44	215.43±2.73	4.12±0.05	10.69±1.29	0.006	1.77±0.17
MD21	S03º06.188’ E032º03.693’	46.07±7.35	21.65±0.73	111.32±1.92	158.75±2.14	125.38±4.47	16.34±3.65	10.59±0.55	0	6.12±1.08
MD22	S03º06.214’ E032º03.660’	48.46±4.59	11.81±2.47	70.61±3.97	139.04±7.58	155.45±0.41	8.09±2.61	9.83±2.12	0	1.60±0.34
MD23	S03º06.221’ E032º03.653’	70.48±9.07	18.60±4.35	100.02±2.93	126.54±4.01	134.36±2.61	4.73±0.13	9.59±2.57	3.72	3.96±1.99
MD24	S03º06.218’ E032º03.651’	61.55±3.29	15.40±2.79	125.15±1.89	166.81±6.47	131.96±2.54	6.28±1.43	8.78±2.65	0	3.24±1.20

Site ID	Location coordinate	Mean elemental concentration (mg/kg)								
		Cr	Co	Ni	Cu	Zn	As	Cd	Hg	Pb
MD25	S03º06.219' E032º03.659'	47.23±0.92	26.92±0.52	91.73±2.12	179.60±5.55	116.52±1.67	11.68±2.85	14.09±1.64	0	6.41±1.00
MD26	S03º06.220' E032º03.673'	39.39±7.30	21.99±2.80	99.40±1.71	130.91±0.82	130.18±0.60	36.11±5.98	7.48±2.10	0	2.45±0.35
MD27	S03º06.216' E032º03.672'	37.32±10.92	11.75±3.26	87.30±8.98	145.26±2.27	117.06±1.89	20.76±3.43	6.98±1.07	0	4.55±0.34
MD28	S03º06.210' E032º03.680'	52.61±3.45	19.24±1.26	73.44±1.66	153.28±4.94	58.02±.04	11.68±3.19	7.98±2.16	0	8.64±0.64
MD29	S03º06.217' E032º03.686'	56.16±7.70	14.91±1.15	131.61±2.75	173.34±1.39	141.79±2.03	34.49±5.86	7.98±2.20	0	2.29±0.72
Minimum		34.45±2.09	10.63±2.27	44.65±4.77	51.86±2.86	58.02±.04	0	6.03±0.01	0	1.60±0.34
Maximum		113.23±4.34	26.92±0.52	131.61±2.75	737.66±1.30	215.43±2.73	36.11±0.47	9.83±2.12	3.72	18.32±1.53
Overall mean for all sampling sites		54.15±4.56	17.75±2.73	96.82±3.81	177.16±3.29	136.76±2.22	12.73827586	7.86±1.03	0.07	6.03±0.91

The results from this study showed variations in concentrations of trace elements for the MDs. The average levels of trace elements in the MDs varied in an increasing order from Cu with the highest-level ranging from 51.86 ± 2.86 – 737.66 ± 1.30 mg/kg with an average value of 177.16 mg/kg to Hg with the lowest levels between 0 to 3.72 mg/kg equivalent with an average value of 0.07 mg/kg. The trend of the intermediate elements showed a clear Zn > Ni > Cr > Co > Cd > Pb > As > Hg, increasing elemental concentrations with levels ranging from 44.65 ± 4.77 – 131.61 ± 2.75 mg/kg averaging 136.76 mg/kg for Zn; 44.65 ± 4.77 – 131.61 ± 2.75 mg/kg averaging to 96.82 mg/kg for Ni; 34.45 ± 2.09 – 113.23 ± 4.34 mg/kg averaging 54.15 mg/kg for Cr; 10.63 ± 2.27 – 26.92 ± 0.52 mg/kg averaging to 17.75 mg/kg for Co; 0 – 6.36 ± 2.07 mg/kg averaging 7.86 mg/kg for Cd; 1.60 ± 0.34 – 18.32 ± 1.53 mg/kg) averaging 6.03 mg/kg for Pb; and 0 – 36.11 ± 0.47 mg/kg) averaging to 12.74 mg/kg for As, respectively. Lower levels of Cd, As and Pb than other trace elements in the MDs could be attributed by the presence of water in the MDs (field observation) which might be increasing the level of sulfuric acid. Sulfuric acid in rocks might be the reason of dissolving Cd, As and Pb hence being discharged through other openings (Schmiermund & Drozd, 1997).

4.3.2 Trace Element Concentrations in Washing Areas

The levels of trace elements in WA varied in an increasing order of concentration levels with the pattern of: Cu > Zn > Ni > Cr > Co > As > Pb > Cd > Hg (Fig. 10-12), Appendix 1 further gives a clear summary including their mean values. The concentration levels recorded for each element was as follows: Cu (74.17 ± 2.58 – 178.97 ± 2.46 mg/kg) averaged 140.99 mg/kg, Zn with average of 115.46 mg/kg ranging from 39.78 ± 0.74 – 145.75 ± 6.84 mg/kg; Ni (46.49 ± 1.50 – 101.68 ± 3.31 mg/kg) with the average 83.59 mg/kg; Cr varied from 49.39 ± 4.91 – 120.19 ± 8.98 mg/kg with average value of 77.59 mg/kg; Co (10.09 ± 0.90 – 38.73 ± 12.19 mg/kg) averaged 21.28 mg/kg; As (6.49 ± 2.20 – 24.09 ± 1.35 mg/kg) with average value of 12.44 mg/kg; Pb (2.45 ± 0.20 – 17.54 ± 1.31 mg/kg) with the average value of 9.95 mg/kg; Cd levels ranging from 0 – 8.77 ± 1.05 mg/kg having the average value of 6.34 mg/kg; and Hg with the average of 0.05 mg/kg ranging from 0 to 0.053 mg/kg, respectively.

Trace elements Cr, Co, and Ni behaved differently in WA (Fig. 10). Cr and Ni were observed to have higher values in WA4 than other sampling points. This observation might probably be attributed by the presence of nickel-chromium compounds such as chromium-nickel oxides ($NiCrO_4$) in the sampled soil. The Co was seen to have approximately equal values in all sampling point with the highest value detected in WA14. This observation might be suggesting that Co came from the same pollution source.

Cobalt was detected in low quantity in WA. This might be attributed to moderately low deposit of materials which comprise this trace element. Also, the washing processes as seen in plates 13 and 14 could be a factor for low level of Co. This is in harmoniousness with the findings reported by Oladele *et al.* (2019) that sedimentation, flow, and transportation contribute to Co removal.

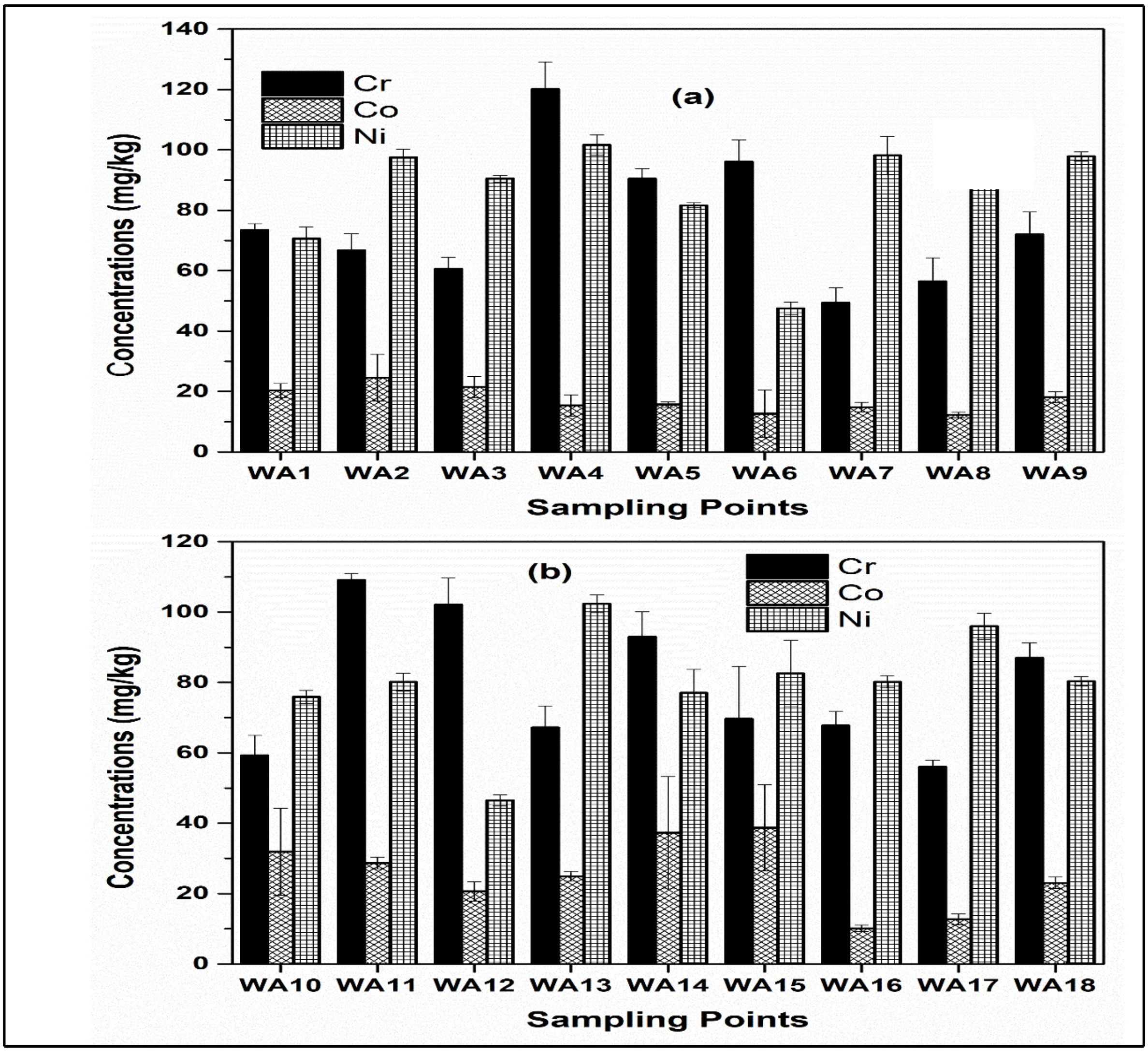


Figure 10: Trends of Cr, Co, and Ni Concentrations in soil collected from washing area A (WA) of the study area

It is important to remark that in Fig. 11 higher and lower values of Cu and As, respectively were obtained in WA13. This observation could probably be explained by the absence of arsenic rich parent rocks in the mining pit to which the soil was sampled. The WA7 and WA8 were seen to have the values of Cu with approximately equal magnitude. Likewise, values of Cu in W15 and W16 have nearly same concentrations. This observation could be due to the closeness of the sampled points.

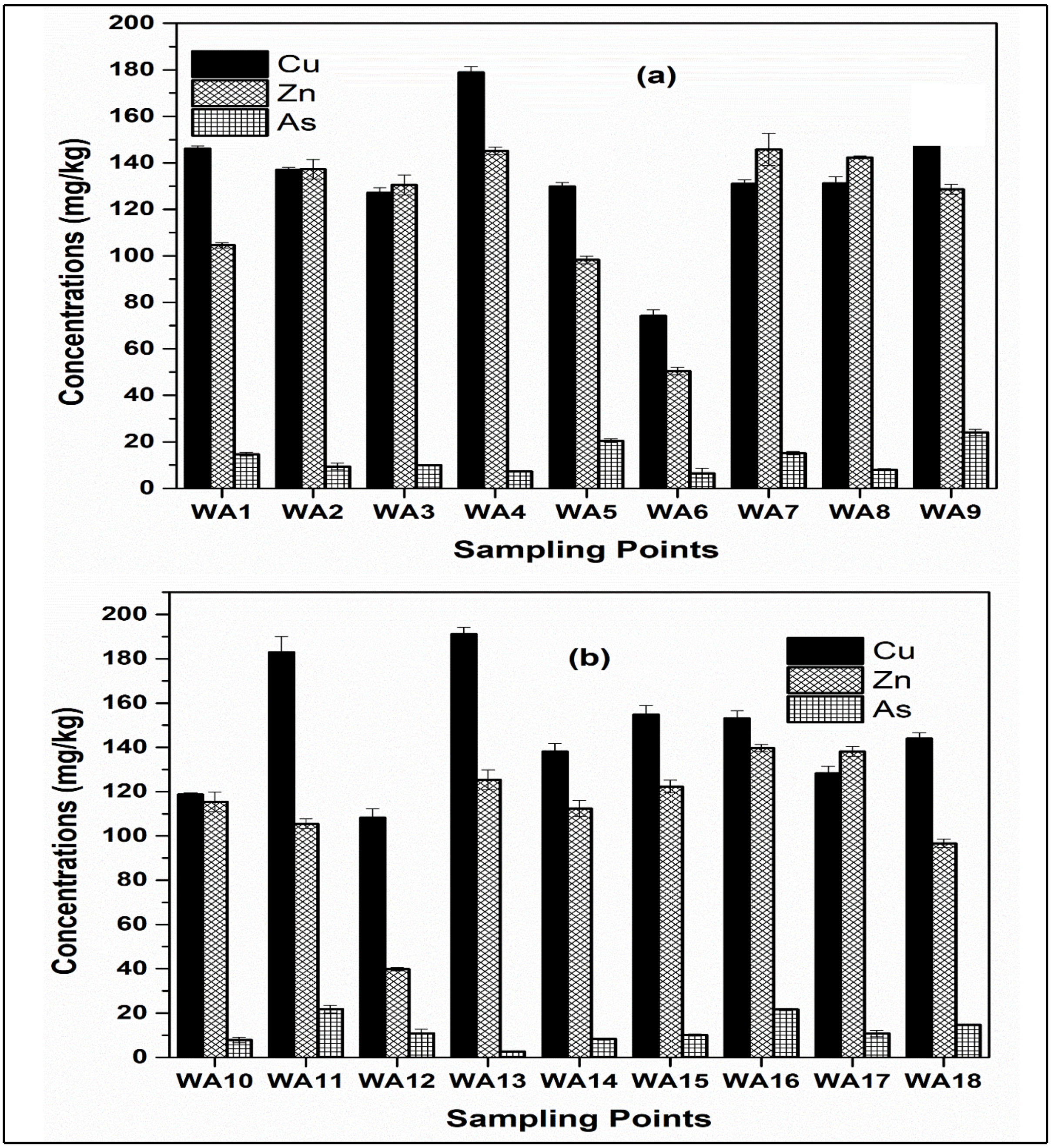


Figure 11: Differences in Cu, Zn, and As Concentrations in soil samples taken from WA of the study area

Trace elements Cd, Hg and Pb in WA were detected in small amounts (Fig. 12). The Hg was not detected in this sampling category. This observation might be suggesting that material washers at WA were not using Hg. Also, it was noted that Cd was not detected at WA11 while Pb was detected maximum at this sampling point.

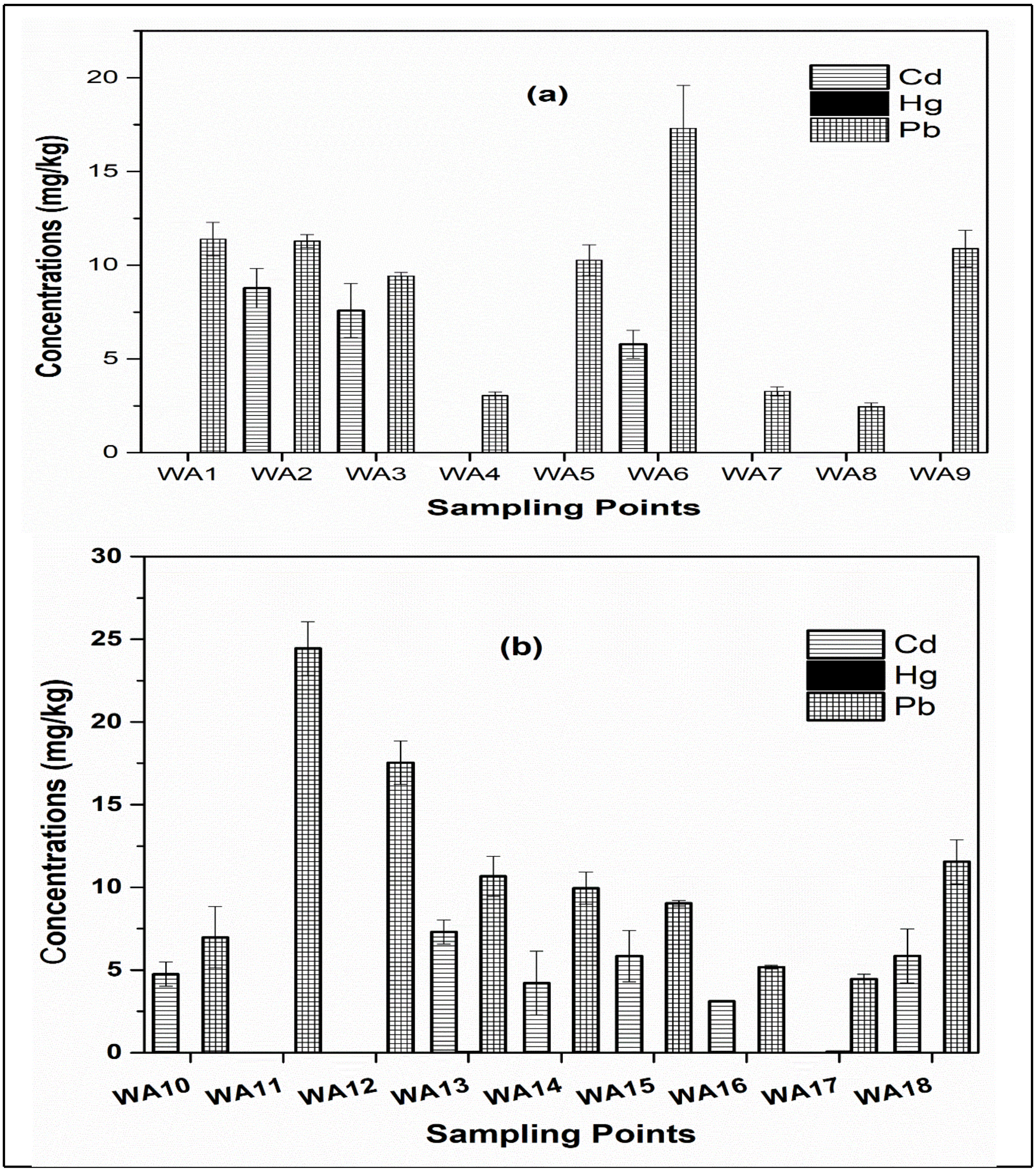


Figure 12: Contrasts in Cd, Hg and Pb Concentrations in soil samples taken from WA of the study area

Generally, from Fig. 10, 11 and 12 it is noted that the most carcinogenic elements (Cr, As and Cd) were found in higher concentrations in the washing areas. Also, the most non-carcinogenic elements (Cu and Pb) have been detected in sufficient quantities. On the other hand Cd and Cr were reported to contribute to both carcinogenic and non-carcinogenic effects (WHO, 2011) and have been detected in significant amounts in this study. This implies that the workers at WA might be having double health impacts (carcinogenic and non-carcinogenic effects). As argued earlier, the working environment and lifestyle in the study area might accelerate the health problems to different groups. The presence of these carcinogenic and non-carcinogenic elements might cause serious health problems to these groups. For example, the prolonged ingestion of Pb to the pregnant women may result in having a mental retarded newborn child (WHO, 2011). Also, long term exposure to Pb by children is reported to cause mental retardation (WHO, 2011). Therefore, there is a need to help these innocent group (women and children) who do not know the future of their health in Rwamagasa ASGM.

The concentrations of trace elements in WB (Fig. 13-15) varied and increased in the order: Cu > Zn > Cr > Ni > Co > As > Pb > Cd > Hg with the average value of 137.38 mg/kg for Cu ranging from 74.71 ± 3.86 – 230.66 ± 3.99 mg/kg; Zn (66.91 ± 2.68 – 157.85 ± 3.63 mg/kg) with the average of 98.78 mg/kg; Cr varied from 45.73 ± 2.86 – 280 ± 12.45 mg/kg having the average of 94.22 mg/kg; Ni (51.74 ± 1.71 – 105.59 ± 0.79 mg/kg) averaged to 72.19 mg/kg; Co (9.2 ± 0.76 – 36.76 ± 5.72 mg/kg) with the average value of 20.68 mg/kg; As with average value of 20.31 mg/kg with levels between 8.17 ± 1.29 – 60.54 ± 1.16 mg/kg; Pb (2.78 ± 0.48 – 34.19 ± 2.52 mg/kg) with the average 12.82 mg/kg; Cd varied from 0 to 8.48 ± 1.63 mg/kg with average of 6.98 mg/kg; and Hg with average concentration of 3.41 ± 0.69 mg/kg, respectively.

The levels of Cr and Co were recorded minimum in WB15 (Fig. 13). This observation might be attributed probably by the absence of acidic pH which could lead the release of Cr and Co ions from the transition metals (Scharf *et al.*, 2014). Also, probably WB15 lacked some oxides such as Cr_2O_3 that could lead to the increased amount of Cr. It was further noted that Cr was detected maximum above 200 mg/kg in two points, WB5 and WB6. This observation could be explained by the fact that the two points were very close to each other. Furthermore, approximately equal values of Cr were detected in WB3 and WB4.

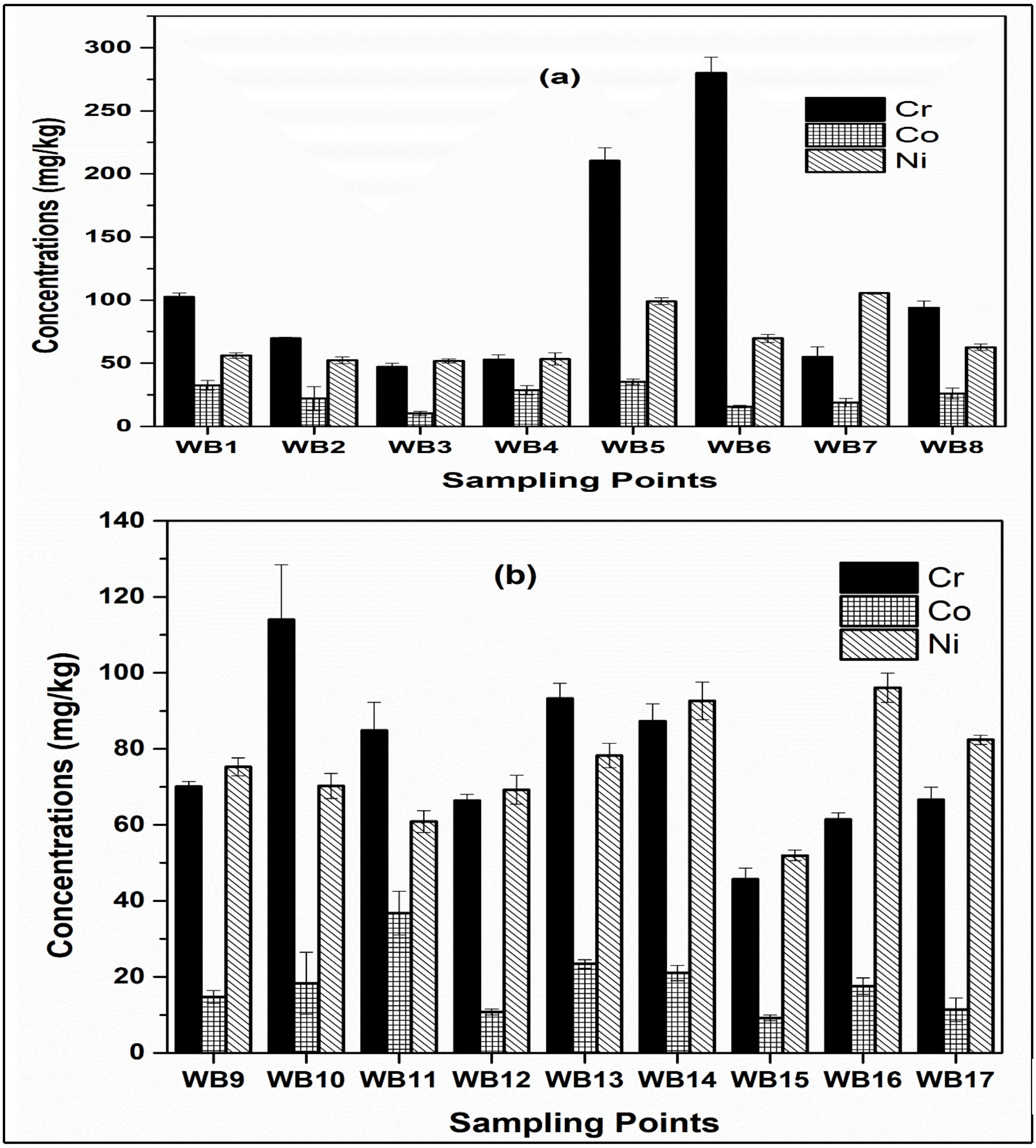


Figure 13: Variations of Cr, Co, and Ni Concentrations in in soil sampled from washing area B (WB) of the study area

Arsenic was detected in small values compared to Zn and Cu in all sampling points (Fig. 14). This observation could be explained by the fact that probably, in WB, there was a high release of O_2 subject on its accessibility in soil and waterlogging. Due to O_2 release, ferrous iron (Fe^{2+}) gets oxidized to ferric iron (Fe^{3+}) (Awasthi *et al.*, 2017). The hydroxides and oxides of iron are reported to be strong sorbent material for As (Awasthi *et al.*, 2017). This phenomenon could lead to small amounts of As recorded in WB. It was further noted from Fig. 14 that Cu and Zn had approximately equal values in WB3 and WB16 and the highest value of Cu was detected in WB6. Approximately equal values of Cu and Zn in WB3 and WB16 might be suggesting that in these points, these elements had same geological characteristics.

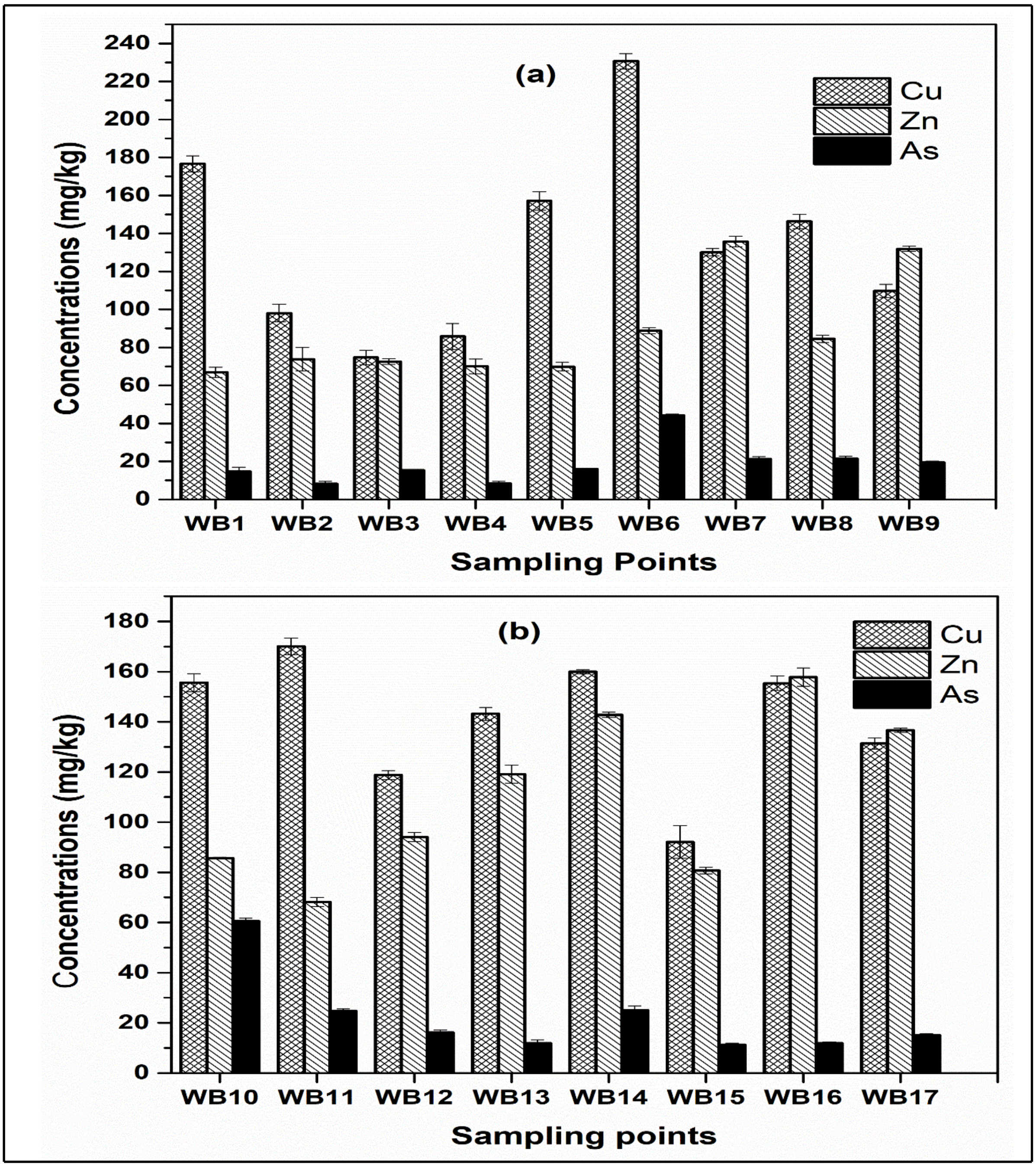


Figure 14: Differences in Cu, Zn, and As Concentrations in soil sampled from WB of the study area

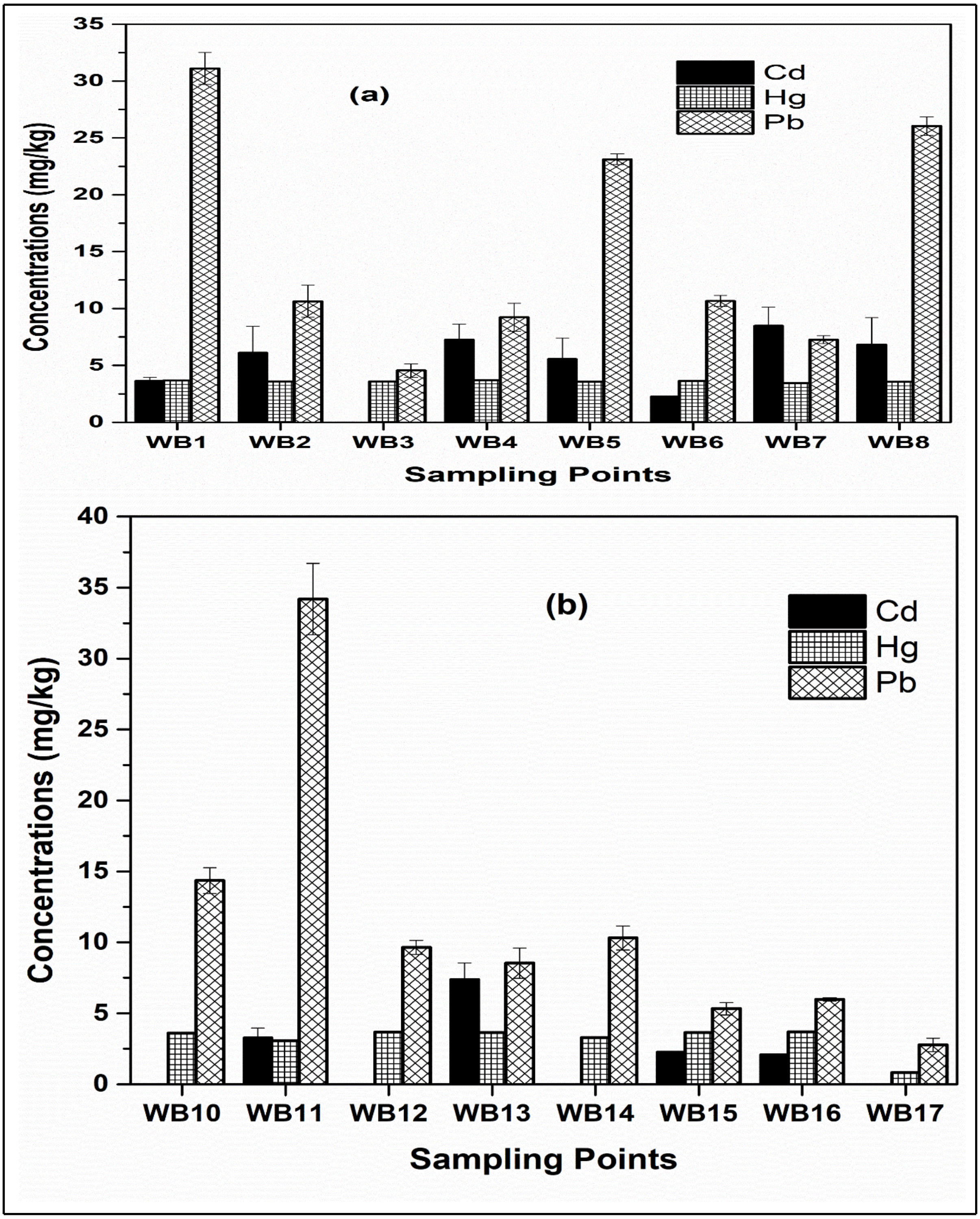


Figure 15: Trends of Cd, Hg, and Pb Concentrations in soil taken from WB of the study area

Generally, field observation showed that the mined material washing process at Rwamagasa started at WA re-washing at WB. The Hg was detected in negligible amounts of (mean = 0.05 mg/kg) at WA (Fig. 12 (bars not seen) and Appendix 1) but surprisingly Hg was detected a high amount of (mean = 3.41 ± 0.69 mg/kg) at WB (Fig. 15 and Appendix 2). This observation might be suggesting that at WB soil washers used Hg during gold recovery. Concentrations higher than standard were detected at WB (WHO, 2011). Apart from detecting high level of Hg at WB, the point of concern is also the working environment of soil washers at Rwamagasa (plates 13, 14, 16 and 17). Working with materials having such level of Hg without any protection is questionable to the health effect awareness to the workers. Health effects such as insomnia, neuromuscular change and headache, memory loss and emotional instability have been reported to be caused by exposure to Hg (Ottenbros *et al.*, 2019). Children who happen to play with the soil at the study area might be the most affected group. Even if different nations are fighting to end the use of Hg in the mining industry, but the use of Hg in the ASGM subsectors especially in the sub-Saharan countries has rest to be the favorite means in gold recovery processes. This might be attributed by its affordability, accessibility, and applicability in the local environments.

4.3.3 Comparison of Trace Element Levels

In comparison, 5 elements (Cr, Cu, Zn, As and Hg) out of 9 analyzed elements showed higher values in MD, WA and WB than in control area (C) (Fig. 16-18). Similar observation was reported by Li *et al.* (2014) in China gold mines. High value of Hg in other sampling categories as compared to C had also been evidenced in many studies (Bose-O'Reilly *et al.*, 2009; Ikingura & Akagi, 1999; Ikingura *et al.*, 2006; Kpan *et al.*, 2014; Ngole-Jeme *et al.*, 2018). This observation further suggests that probably there is link between gold and Cr, Cu, Zn and As. The levels in C were also in an increasing pattern, in the order: Cu > Ni > Zn > Cr > Co > Pb > Cd > As > Hg (Fig. 16-18). The concentrations measured from C samples include Cu (60.84 ± 1.72 – 141.16 ± 3.84 mg/kg); Ni (50.81 ± 2.52 – 123.15 ± 0.33 mg/kg); Zn (34.48 ± 1.74 – 160.75 ± 3.19 mg/kg); Cr (40.09 ± 2.26 – 56.576 ± 4.62 mg/kg); Co (8.87 ± 1.09 – 30.21 ± 2.63 mg/kg); Pb (11.45 ± 0.74 – 16.46 ± 0.65 mg/kg); Cd (6.86 ± 1.84 – 9.27 ± 1.13 mg/kg); As (0 – 5.14 ± 0.56 mg/kg). Note that Hg was not detected in C samples that were investigated. The Ni and Cu showed high amount in the C category. The high level of Cu in the C might also be attributed by anthropogenic sources such as fungicides, and agricultural pesticides used as domestic materials. The lower values of trace elements in C as compared to the samples from MP, WA and WB suggest that the mining activities influence the levels of trace elements.

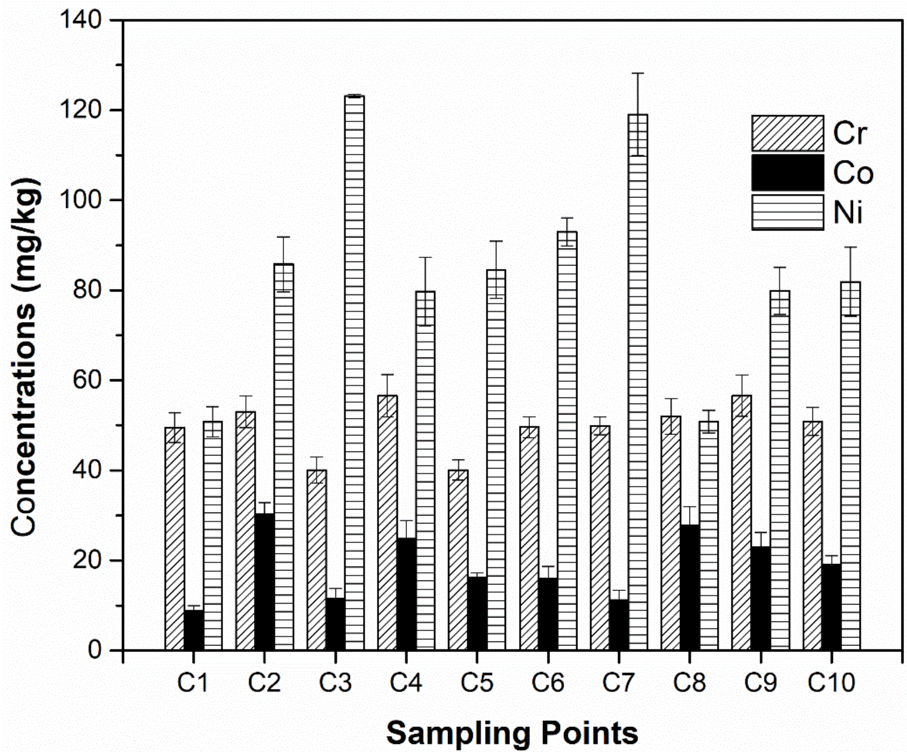


Figure 16: **Cr, Co and Ni concentrations in in soil samples collected from the control Area**

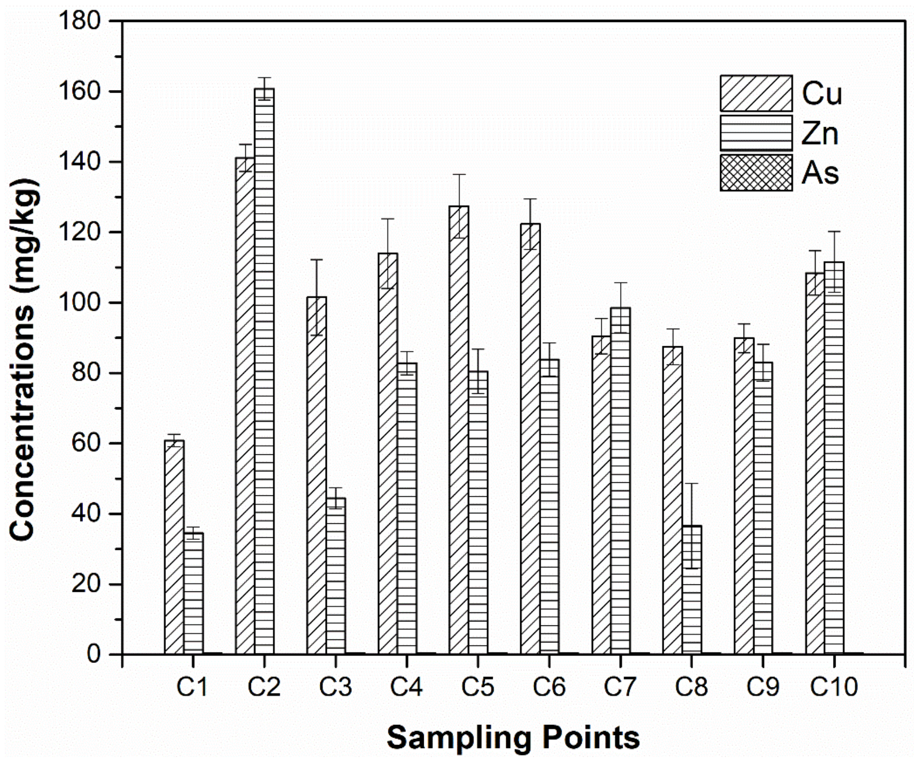


Figure 17: **Cu, Zn and As concentrations in soil samples taken from the control Area**

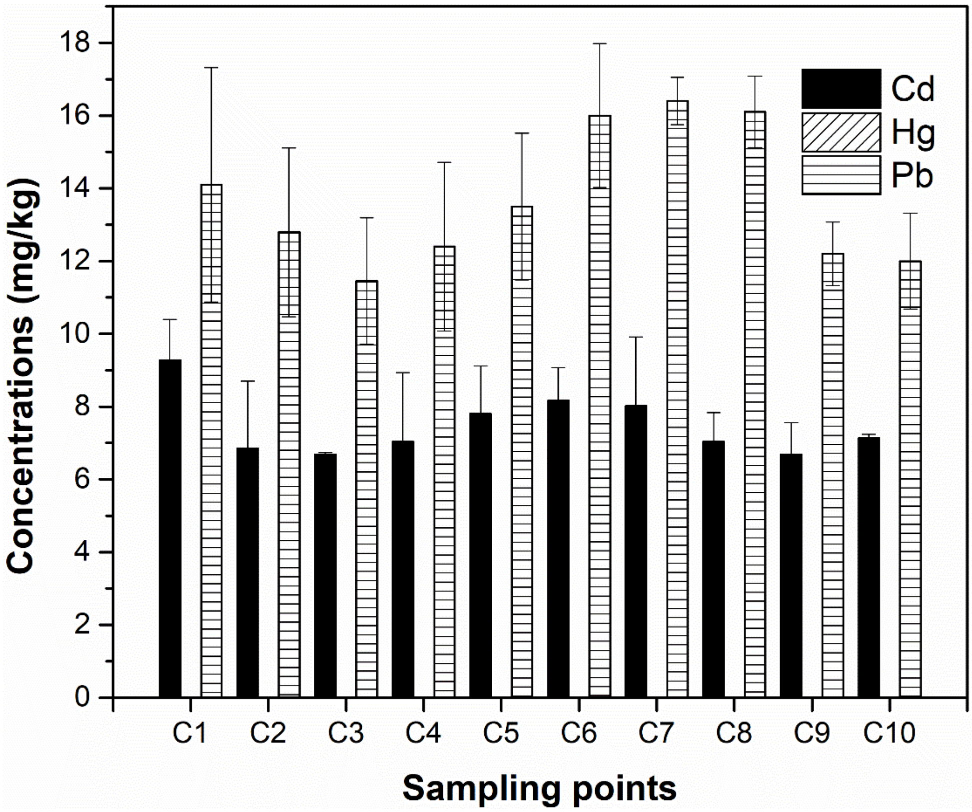


Figure 18: Cd, Hg and Pb concentrations in in soils sampled from the control Area

Generally, Hg was not detected in the C samples but was found to have average values of 3.41 ± 0.69 mg/kg in samples from WB, 0.05 ± 0.11 mg/kg for the WA, and 0.07 ± 0.15 mg/kg in the MDs. These high Hg levels in the WB were in good agreement with an earlier study that showed high levels of Hg in bio-monitored blood, urine, and hair from residents at Rwamagasa (Bose-O'Reilly *et al.*, 2009). The recorded levels of trace elements at MD, WA, and WB differed from levels recorded in C suggested that anthropogenic activities e.g. mining do influence the concentration and distribution of trace elements in different micro-environments. Arfaeinia *et al.* (2016) found that the levels of trace elements were high in samples from industrial areas as compared to samples from urban environments, which is in line with the present study.

4.4 Soil Risk Assessment

4.4.1 Non-carcinogenic Risk Assessment

The non-carcinogenic risk for residents in the study area was evaluated based on children and adults using the stipulated *RfD* values shown in Table 7 and *ADI* values presented in Table 10. The calculated values for the inhalation, ingestion, and dermal pathways are all presented in Fig. 19 (a-d) in terms of HQs.

Table 10: Average Daily Intake values in soil from the study area for noncancer risk

Receptor	Pathway	Average daily intake for trace elements (x 10^{-6} mg/kg/day)								
		Cr	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Cd**	**Hg**	**Pb**
Child	Inhalation	0.037	0.009	0.041	0.075	0.058	0.005	0.003	0.001	0.005
	Ingestion	963	254	1080	1940	1500	140	90.3	16.4	123
	Dermal	123	32.6	138	249	192	17.9	11.6	2.1	15.7
	Total	1090	287	1210	2190	1690	157	102	18.5	138
Adult	Inhalation	0.0159	0.004	0.018	0.032	0.0247	0.002	0.001	0.0003	0.002
	Ingestion	103	27.3	115	208	160	15	9.67	1.75	13.2
	Dermal	25.6	6.75	28.6	51.5	39.7	3.7	2.4	0.434	3.26
	Total	129	34	144	260	200	18.7	12.1	2.19	16.4

The Average Daily Intake (ADI) values in soil for non-carcinogenic effects (Table 10) indicated more effects on children than adults. For the three exposure routes considered, the total ADI was much greater for children than adults for the nine trace elements investigated. This indicated that children were more prone to non-carcinogenic risks than adults. These higher levels of ADI in children might be due to their living behaviors. In a different study, contaminated soils were found to pose more risk to children than they did to the adult members in a small-scale mining community (Kamunda *et al.*, 2016). The authors (*ibid*) also indicated that for both children and adults the ingestion pathway contributed highly to the noncancer risks followed by the dermal contact pathway. A similar trend was followed when carcinogenic effects were considered, with children at a higher risk than adults and ingestion being the dominant pathway.

The values (bars) of the HQs and cancer risks for some trace elements did not show up on the plots (Fig. 19 and 20). This was because some elements such as As, Cd, Cu, Hg, Pb and Zn were detected in small values compared to Co, Cr and Ni. However, frequent, and long-term exposure to even small amounts of carcinogenic elements such as As, Cd, Hg and Pb may still cause serious human health problems (Focus *et al.*, 2021; Kabata-Pendias, 1993).

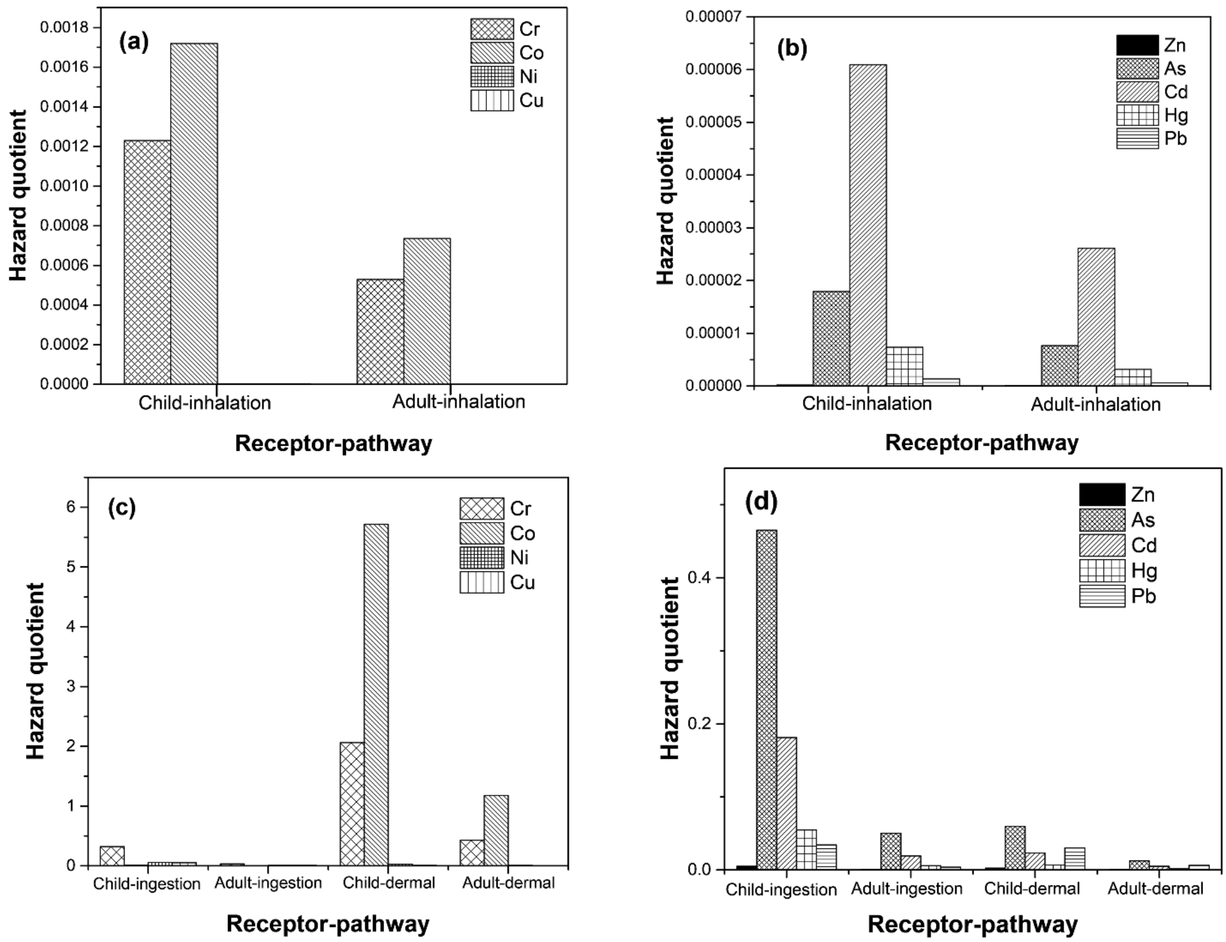


Figure 19: Hazard quotient values of selected trace elements for children and adults through the inhalation pathways (a and b) and via the ingestion and dermal pathways (c and d) in soil collected from the study area

4.4.2 Carcinogenic Risk Assessment

The average dose intake in estimating the excess lifetime cancer risks for children and adults are presented in Table 11. The lifetime cancer risk analysis results are presented in Fig. 20 (a-d).

Table 11: Average daily intake (ADI) of soil samples from the study area for carcinogenic risk

Receptor	Pathway	Average daily intake for trace elements (x 10^{-6} mg/kg/day)								
		Cr	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Cd**	**Hg**	**Pb**
Child	Inhalation	0.003	0.001	0.004	0.01	0.01	0.001	0.0003	0.0001	0.0004
	Ingestion	82.5	21.8	92.3	166	128	12	7.74	1.4	10.5
	Dermal	10.6	2.79	11.8	21.3	16.4	1.53	0.991	0.18	1.35
	Total	93.1	24.6	104	188	145	13.5	8.73	1.58	11.9
Adult	Inhalation	0.007	0.002	0.008	0.02	0.01	0.001	0.001	0.0001	0.001
	Ingestion	44.2	11.7	49.4	89.1	68.7	6.41	4.14	0.751	5.64
	Dermal	11	2.89	12.2	22.1	1.59	1.59	1.03	0.186	1.4
	Total	55.2	14.6	61.7	111	8	8	5.17	0.938	7.03

The cancer possibility was calculated based on the nine trace elements. As shown in Fig. 20, As and Cr were found to be the most contributors to the cancer risk. The United States Environmental Protection Agency (USEPA) considers tolerable value for monitoring purposes a cancer risk of 1 x 10^{-6} (Kamunda *et al.*, 2016). However, Tanzania has not yet developed the acceptable range for cancer risk regulatory purposes. In the present study, the carcinogenic risks for adult and child population were found to be 3.42 x 10^{-5} and 6.16 x 10^{-5}, respectively, which are higher than the tolerable limit (1× 10^{-6}). The results obtained from the present study show that children were consequently more at risk than adults. With the trace elements considered, the results indicated that soils collected from WB had higher levels of trace elements compared to the soils from MP, WA and C (Table 9; Fig. 10-15).

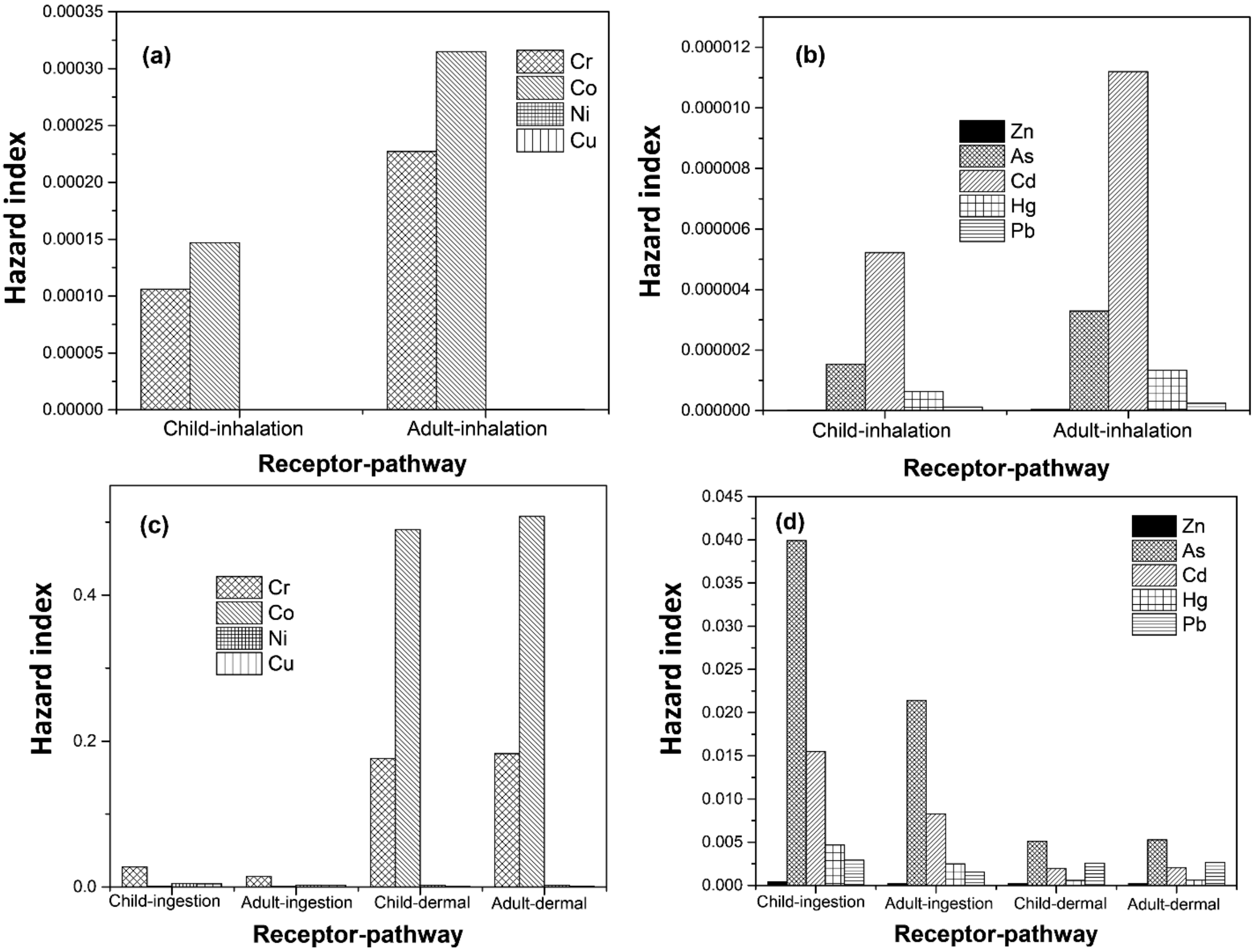


Figure 20: Cancer hazard indices of selected trace elements for children and adults through inhalation pathways (a and b) and through ingestion and dermal pathways (c and d) in soil from the study area

4.4.3 Trace Element with Permissible Levels: A comparison

Based on the suggested maximum permissible limits for Tanzania and other countries (Table 12), the present study revealed higher concentrations of Cu, Co, Zn, and Cr (Fig. 15 and Appendix 2). The Pb, Cd, Hg had lower values less than the maximum allowable limits. However, the average value of 3.41 ± 0.69 mg/kg for Hg in WB was much higher than the recommended limits by international organizations and countries except the United Kingdom (Tipping *et al.*, 2011) which recommends a limit of 10 mg/kg. This high level of Hg in WB rises a point of concern to the responsible regulatory authorities.

Table 12: Allowable limits for trace element concentrations in soil (mg/kg) for different countries/organizations

Country/ organization	Maximum allowable limit[a]										
	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Hg	Pb
Tanzania	100	1.5	N.I.	N.I.	100	200	150	1	1	2	200
US EPA	11	N.I.	N.I.	270	72	N.I.	1100	N.I.	0.43	N.I.	200
FAO/WHO	100	N.I.	N.I.	50	50	100	300	20	3	N.I.	100
EU	75	140	300	N.I.	3	100	1	N.I.	3	N.I.	300
China	200	N.I.	N.I.	N.I.	50	100	250	30	0.5	0.7	80
Canada	250	N.I.	N.I.	N.I.	100	150	500	20	3	0.8	200
Bulgaria	65	N.I.	N.I.	20	46	34	88	10	0.4	0.03	26
UK	130	N.I.	N.I.	N.I.	130	N.I.	N.I.	32	10	10	450
Australia	50	N.I.	N.I.	N.I.	60	100	200	20	3	1	300
German	60	N.I.	N.I.	N.I.	50	40	150	50	1	0.5	70
Poland	100	N.I.	N.I.	50	100	100	300	N.I.	3	N.I.	100

Kamunda *et al.* (2016)

[a]N.I. = not indicated

Generally, a large body of literature indicates that when the HQ and HI values are less than 1, there is no evident risk to the residents (Karim & Qureshi, 2014; Zheng *et al.*, 2007), but if these values exceed unity, there may be concerns for possible non-carcinogenic and carcinogenic effects (Islam *et al.*, 2021; Karim & Qureshi, 2014). The total calculated HQ values for all elements for adults were less than one in the inhalation and ingestion routes, whereas the value of 1.64 was found for the dermal pathway. The observed high value through the dermal pathway may be indicative of a noncancer risk to the miners, soil washers, and residents at study area. The hazard index for all pathways was equal to 1.77. This suggested that the residents are at the threat of non-carcinogenic effects. For children, the dermal and ingestion paths had HI and HQ values greater than 1, mostly driven by Cr and Co and gave a total HI of 9.11 for all three routes. This high value indicated trace element pollution that may pose an appreciable noncancer health risk to children living around the Rwamagasa ASGM. These results were in good agreement with previous findings (Kamunda *et al.*, 2016; Ngole-Jeme & Fantke, 2017). The results also indicated that, for both adults and children, the dermal pathway adds the greatest to the non-carcinogenic risk, followed by the ingestion pathway, while inhalation was the least contributor to the risk as shown in Fig. 19.

4.5 Soil Radioactivity

4.5.1 Radionuclide's Concentrations

The results of the average activity levels of ^{238}U, ^{232}Th and ^{40}K are presented in Fig. 21. Also, the detailed information of geo-references, activity concentrations, minimum and maximum values of soil radionuclides from different sampling points are presented in Appendix 4.

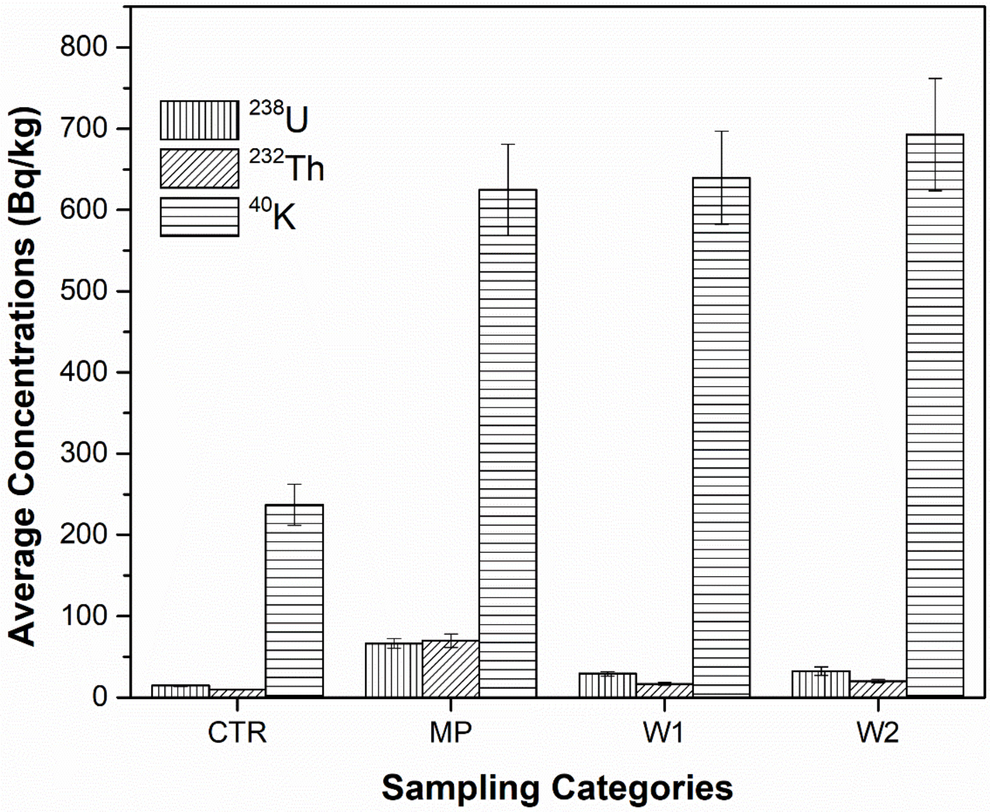


Figure 21: Activity levels of ^{226}Ra, ^{232}Th and ^{40}K from the control and mining areas sampling categories

Results in Fig. 21 show that, higher levels of ^{238}U and ^{232}Th were detected in MP than in W1, W2, and CTR. This observation might be due to the fact that ^{238}U and ^{232}Th are expected in the phosphate rocks, therefore, probably the area has the uranium-and thorium-rich rocks (Mohammed & Mazunga, 2013). Furthermore, it is noted in Appendix 4 that the highest activity concentration of ^{238}U was detected in MP-1 (95 Bq/kg) and the highest activity of ^{232}Th with almost the same magnitude (96.2 Bq/kg) was detected in the same MP (MP-1). This observation might be due to the chemistry of ^{226}Ra, ^{232}Th and ^{238}U that, as ^{232}Th disintegrates, gives radiation and produce decay daughters that include ^{228}Th and ^{228}Ra (Sarin *et al.*, 1990). As shown in Fig. 21 and Appendix 4, the average activity concentration of ^{238}U in the MPs was 42.59 Bq/kg while in CTR the activity of ^{238}U was 14.45 Bq/kg. For ^{232}Th, the average activity concentrations were 35.48 Bq/kg and 9.67 Bq/kg in MP and CTR areas, respectively. The mean activity of ^{40}K in the mining area was 652.36 Bq/kg while in CTR was 236.84 Bq/kg.

It was further noted in Fig. 21 that the concentrations of radionuclides were mostly higher in the MP, W1 and W2 than in CTR category. This observation may confirm the findings reported in the literature that mining activities, if not well controlled, elevates the radioactivity levels in the environment (Ademola & Obed, 2012; Aliyu *et al.*, 2015; UNSCEAR, 2020). The implication of this is that mine workers and the public could be at risk. Also, in the present study, field observation discovered that mined soil was not wetted, which might lead to this increment of radionuclides in the MP, W1 and W2 (Ghose & Majee, 2001). The blasting of rocks, transportation of mined materials might be contributing to the high level of radionuclides. The activity levels of ^{238}U and ^{40}K in MP, W1 and W2 were higher than the world recommended values of 35 Bq/kg and 420 Bq/kg, respectively. In contrast, the concentration of ^{232}Th was lesser than the world mean value of 45 Bq/kg (Esiole *et al.*, 2019) but 25% higher than a control value which alerts the need for radiation protection and control strategies. In the CTR, all the values were lower than the world recommended levels (Ademola & Obed, 2012). Frequent exposure to radionuclides has negative health impacts to different organs. For example, the fast growing cells and cell divisions to children and the most sensitive parts to radiations for women (breasts) are reported to be affected more by radiations (Brusin, 2007; Tomà *et al.*, 2019).

4.5.2 Radiological Hazard Assessment for Soil Samples

Using Equation (8), the dose rates (Ds) were estimated using the activities of ^{40}K, ^{232}Th and ^{238}U and presented in Fig. 22 (a). It was assumed that the contribution from other naturally occurring radionuclides and cosmic radiation at the locations were insignificant as reported elsewhere (ICRP, 2019). Based on Equation (9), the effective doses (Es) were estimated, and their averages are presented in Fig. 22 (a); Fig. 22 (b) and 22 (c) present other calculated radiation indices.

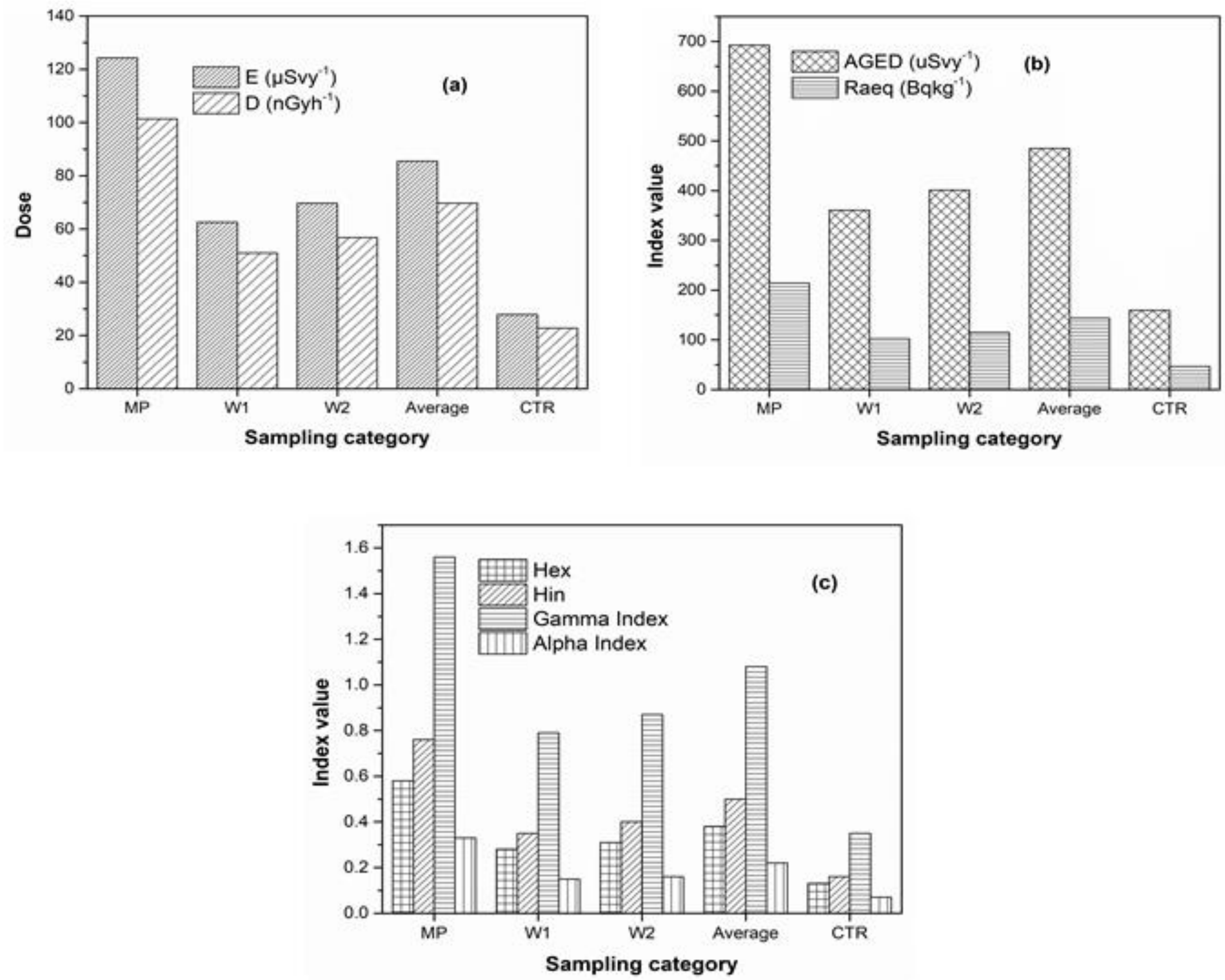


Figure 22: Mean effective dose and absorbed dose rate (a), the annual gonadal equivalent dose and radium equivalent (b), internal hazard index, the external hazard index, gamma index and alpha index (c) from the study area

The average dose rates in MP, W1 and W2 (Fig. 22) were 101.36; 50.99; and 56.83 nGy/h, respectively. The overall average Ds in the MP, W1 and W2 was 69.73 nGy/h while in CTR was 22.76 nGy/h. The dose rates estimated for the MP, W1 and W2 were higher than the world suggested mean value of 60 nGy/h (UNSCEAR, 2000). It was noted that the results of the dose rates from the study area were in the ratio of 1.6 times higher than the world permissible value. It was further shown that the values from the CTR were 4, 2 and 2 times lower than the values obtained in the MP, W1 and W2, respectively. These incremental values might be hazardous to the public and workers who work, and others live within the study area. Also, high doses in the MPs might affect miners especially men who work long hours in the MPs during material mining at Rwamagasa ASGM. For example, gonads are reported to be more affected by radiations (Howell & Shalet, 1998). The average effective doses in MP, W1and W2 were 124.30, 62.54 and 69.69 mSv/y, respectively with the total average of 85.51 mSv/y. The mean effective dose in the CTR category was 27.90 mSv/y. It was well noted from the results that values from the MP, W1 and W2 were higher by 5, 2 and 3 times than the CTR. Lower levels in CTR than in other categories may be indicative of the presence of incremental dose, which could suggest that miners in the study area practice unsafe mining activities. The Ra_{eq} presented in Fig. 22 shows that the mean values estimated in the MP, W1 and W2 and in the CTR were lower compared to the recommended world tolerable value of 370 Bq/kg (UNCEAR, 1982). However, the MPs had an incremental value of 60% greater than the CTR. It has to be noted that what matters in radiation protection is the incremental dose (Pentreath, 2002).

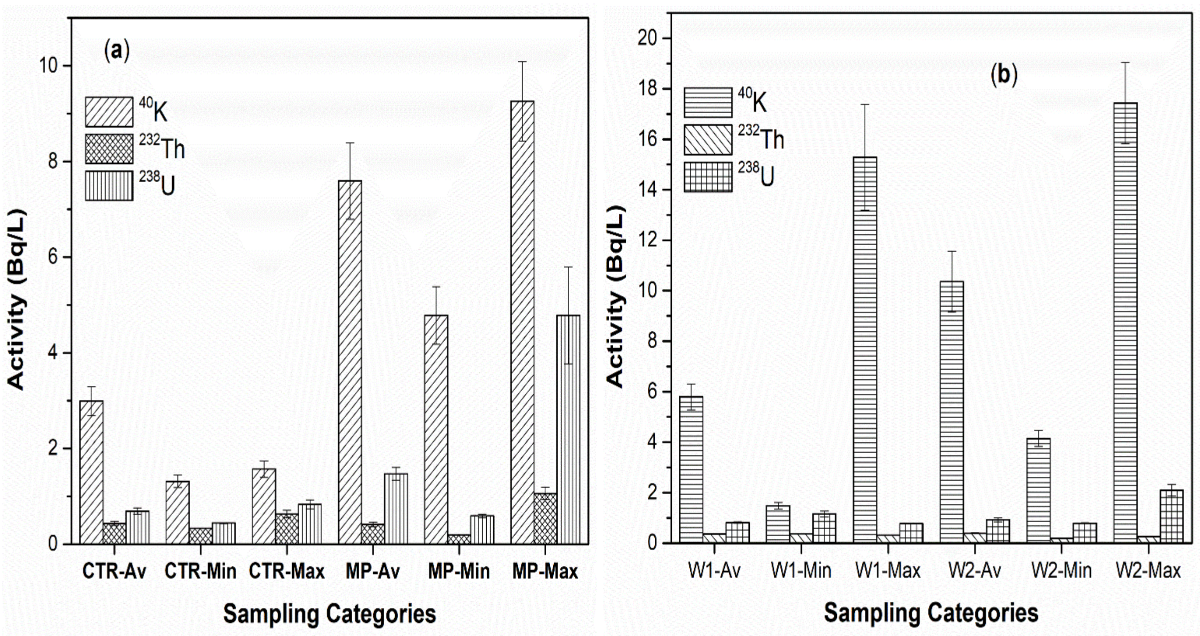
The calculated mean value of H_{ex} (0.5) was lower than unity as suggested by the international organizations (IAEA, 2007; UNSCEAR, 2020). The mean values of $I\gamma$ estimated were above unity in the MPs and below the standard of unity in W1, W2 and CTR. The total average values in the MP, W1, and W2 were above the criterion of unity which is not safe for the workers especially miners who spend more time in MPs. The results for the I_α revealed that all values were below unity. The average value of AGED in the MP, W1 and W2 are 692.65, 360.64 and 400.98 mSv/y, respectively, which were about 5, 3 and 3 times, respectively, higher than the results from the CTR, indicating the influence of mining actives to radionuclide increments. The overall mean value of AGED in MP, W1 and W2 was 484.76 mSv/y which was greater than the world recommended average of 298 µSv/y (UNSCEAR, 2020) and 3.5 times higher than the CTR value. The estimated radiological hazard from the present study calls for the responsible radiation protection and regulatory bodies of Tanzania to work close with the miners and the public at Rwamagasa ASGM in providing adequate education on public, environmental and workplace education.

4.5.3 Soil Radionuclide Levels: A comparison

A study conducted by Munyao *et al.* (2020) from soil samples along Ekalakala River in Kenya reported low average levels of ^{226}Ra (14.3 ± 3.8) Bq/kg and ^{232}Th (17.3 ± 4.2) Bq/kg ranging between 11.5 - 26.2 Bq/kg and 9.7 - 24.0 Bq/kg for ^{232}Th and ^{226}Ra, respectively while ^{40}K had concentration of 1300 ± 300 Bq/kg a value 3 times higher than the world average (UNSCEAR, 1993). In comparison, both studies (Ademola & Obed, 2012; Kamunda *et al.*, 2016) and results from the present study suggest that mining activities contribute to elevated concentration of radionuclides to the natural environment. However, the present study revealed high level of ^{40}K. The field observation at Rwamagasa evidenced small-holder agricultural activities being practiced in the vicinity of the mines. Therefore, higher value of ^{40}K can also be associated to the geology of the area and probably the use of K-enriched fertilizers by farmers around the study area. Further relationship of the results obtained in the present study with studies in literature is presented in Table 13.

Table 13: Comparison of the findings in the present study with other published results elsewhere

Country	Radionuclide			Reference (s)
	^{40}K	^{238}U	^{232}Th	
Australia	114.7 ± 10.7	51.5 ±3.8	48.1 ± 5	Beretka and Mathew (1985)
Algeria	422	41	27	Amrani and Tahtat (2001)
Brazil	564	61.7	58.5	Malanca *et al.* (1993)
Ghana	162.1 ± 63.69	13.6 ± 5.39	24.2 ± 1.75	Faanu *et al.* (2011)
Kenya	69.5 ± 6.1	20.9 ± 1.9	27.6 ± 2	Osoro *et al.* (2011)
Rwanda	267 ± 16.8	515 ± 53.6	57 ± 5.4	Ntihabose (2010)
South Africa	427 ± 39.8	785.3 ± 70.7	43 ± 4.1	Kamunda *et al.* (2016)
Tanzania	564.3 ± 67.6	51.7 ± 5.2	36.4 ± 3.1	Mohammed and Mazunga (2013)
World average	420 ± 19.7	35 ± 2.9	30 ± 2.9	UNSCEAR (2020)
Present study	652.36 ± 61.4	42.59 ± 4.3	35.48 ± 2.9	This study



*AV = Average, *Min = Minimum, *Max = Maximum

Figure 23: (a) Average levels of ^{40}K, ^{232}Th and ^{238}U for water samples from the control and mining pits (b) Average levels of ^{40}K, ^{232}Th and ^{238}U for water samples from the washing areas

4.6 Activities of ^{238}U, ^{232}Th and ^{40}K in Water Samples

Figure 23. (a) and (b) shows the average activity of ^{238}U, ^{232}Th and ^{40}K in water samples. In MPs, the average values for ^{238}U, ^{232}Th and ^{40}K in Bq/L were 1.47, 0.41 and 7.60, respectively. The W1 samples yielded average values of 0.81, 0.36 and 5.80 Bq/L for ^{238}U, ^{232}Th and ^{40}K,

respectively. The average records for ^{238}U, ^{232}Th and ^{40}K in W2 were 0.93, 0.36 and 10.36 Bq/L, respectively. Furthermore, the CTR exhibited average values of 0.70, 0.43 and 3.0 Bq/L for ^{238}U, ^{232}Th and ^{40}K, respectively. The highest concentrations of ^{238}U were measured in water samples from MPs while ^{40}K revealed the highest average value of 10.40 Bq/L in W2.

The results in Fig. 23 further showed that ^{238}U revealed higher values in W1, W2 and MP2 than in the CTR. Appendix 6 presents detailed values for the radionuclides ^{40}K, ^{232}Th and ^{230}U from water samples. Even though the values in W1 and W2 were lower than the permissible limits but these levels were higher than the CTR values. This observation was evidence for the incremental activity. Field observations of the study found residents using water from the MPs for domestic purposes. also, water from the WA and WB areas were used for hand and face washing. Also, it was observed that within the Rwamagasa ASGM, small-scale farming and animal keeping were practiced. If this water is used for irrigation, the effects of radionuclides may further go to the food chain. Also, when animals/birds such as goats, cows and chicken drink such water may lead to human effects through milk and/meet consumption. As recommended in the last chapter of this report, other studies are required in order to have a link between the radioactivity levels with the animal and agricultural products at Rwamagasa ASGM in the efforts of addressing public and environmental health.

4.6.1 Radiological Hazard Assessment

The different computed radiological parameters for water samples from the MP, W1, W2 and CTR are summarized in Table 14. The average Ra_{eq} value in Bq/L from CTR was 1.54, which was lower than the calculated values of 1.98, 1.8 and 2.3 for the MP, W1 and W2, respectively. Maximum amounts were found in water samples collected in the MP. It must be understood that water from the MP were used for domestic activities including cooking, washing clothes and bathing (field observation). This observation is alerting for the public health education to people at Rwamagasa ASGM because prolonged exposure to such water might cause cancer and non-cancer health effects. The average absorbed dose rate owing to ^{238}U, ^{232}Th and ^{40}K in water samples ranged from 0.59 to 0.87 nGy/h, with an average of 0.71 nGy/h in the CTR. In the MPs, an average of 0.93 nGy/h was calculated, with a range of 0.59 to 1.47 nGy/h. The average values for WA and WB were 0.84 nGy/h and 1.10 nGy/h, respectively. Although the estimated average values from the study area were lower than the world average of 59 nGy/h (UNSCEAR, 2000), this does not guarantee health safety to people of Rwamagasa ASGM. In radiation protection, the most important thing is the incremental value which is the value above the background levels (Clarke, 1992). In the present study, the control values were assumed to be as the background values (Pentreath, 2002). The results show clearly that the average absorbed dose rate of radionuclides from water samples collected from MP, W1 and W2 were higher than the value obtained from the CTR. Safe mining practices education must be given to workers at Rwamagasa ASGM for the betterment of public and environmental health. The RC revealed an average value (2.34×10^{-4}) in MPs greater than the value (1.75×10^{-4}) estimated from the CTR area having an increment of 1.4×10^{-4}, this observation informs the need for the control measures.

Table 14: The radiological indices estimated for water samples

Sample ID	RC	AGED (mSv/y)	H_{in}	H_{ex}	Ra_{eq} (Bq/L)	D (nGy/h)	Sample ID	RC	AGED (mSv/y)	H_{in}	H_{ex}	Ra_{eq} (Bq/L)	D (nGy/h)
							$\times 10^{-4}$						
CTR1	1.9	2.17	58.7	37.3	1.38	0.62	W1-1	1.91	2.08	66.1	43.9	1.63	0.77
CTR2	1.44	2.04	54.6	35.4	1.31	0.59	W1-2	1.43	1.78	57.0	41.9	1.55	0.74
CTR3	1.31	1.96	51.4	39.5	1.46	0.67	W1-3	1.84	2.09	85.4	64.6	2.39	1.19
CTR4	2.03	2.38	72.7	50.2	1.86	0.87	W1-4	2.12	2.51	68.3	45.1	1.67	0.76
CTR5	1.78	2.16	64.5	45.3	1.68	0.79	W1-5	1.43	1.88	51.5	36.9	1.37	0.63
Average	1.75	2.14	60.4	41.6	1.54	0.71	W1-6	1.87	2.08	60.9	39.5	1.46	0.67
Minimum	1.31	1.96	51.4	35.4	1.31	0.59	W1-7	2.84	3.06	82.4	49.4	1.83	0.81
Maximum	2.03	2.38	72.7	50.2	1.86	0.87	W1-8	0.63	0.99	48.5	43.6	1.62	0.83
MP1	2.61	2.83	91.3	61.0	2.26	1.07	W1-9	2.7	2.97	79.5	48.4	1.79	0.80
MP2	1.52	1.93	64.3	48.4	1.79	0.86	W1-10	2.9	3.22	99.5	66.3	2.45	1.15
MP3	2.03	2.38	72.7	50.2	1.86	0.87	Average	1.96	2.27	69.9	48.0	1.78	0.84
MP4	2.02	2.18	70.7	47.2	1.75	0.83	Minimum	0.63	0.99	48.5	43.6	1.62	0.83
MP5	1.74	2.04	54.6	35.4	1.31	0.59	Maximum	2.9	3.22	99.5	66.3	2.45	1.15
MP6	4.73	4.75	14.4	86.2	3.19	1.47	W2-1	2.98	3.19	113.1	78.2	2.89	1.40
MP7	1.78	2.16	64.5	45.3	1.68	0.79	W2-2	2.96	4.16	120.8	92.4	3.42	1.61
MP8	2.39	2.62	80.7	53.2	1.97	0.92	W2-3	4.7	4.73	159.8	103.0	3.81	1.82
MP9	1.9	2.17	58.7	37.3	1.38	0.62	W2-4	1.54	1.98	76.2	60.3	2.23	1.11
MP10	2.38	2.47	74.5	46.2	1.71	0.79	W2-5	1.63	1.72	69.1	49.9	1.85	0.92
Average	2.34	2.65	80.1	53.6	1.98	0.93	W2-6	1.46	1.67	52.5	36.1	1.33	0.63
Minimum	1.52	2.04	54.6	35.4	1.31	0.59	W2-7	1.51	1.75	68.9	52.1	1.93	0.96
Maximum	4.73	4.75	143.5	86.2	3.19	1.47	W2-8	1.88	2.37	74.2	54.4	2.02	0.96
							W2-9	1.75	1.87	70.9	50.4	1.86	0.92
							W2-10	1.82	1.95	59.0	37.7	1.39	0.65
							Average	2.22	2.54	86.4	61.4	2.27	1.10
							Minimum	1.46	1.67	52.5	36.1	1.33	0.63
							Maximum	4.7	4.73	159.8	103.0	3.81	1.82

Table 14 shows also the AGED values from MP, W1, W2 and CTR. The values in MP, W1 and W2 ranged from 2.04×10^{-4} to 4.75×10^{-4} mSv/y, with an average of 2.65×10^{-4} mSv/y. The W1 showed values ranging from 9.89×10^{-4} to 3.22×10^{-4} mSv/y, with an average of 2.27×10^{-4} mSv/y. In addition, the W2 had an average value of 2.54×10^{-4} mSv/y, with a range of 1.67×10^{-4} to 4.73×10^{-4} mSv/y. The average values from all three stations were higher than the mean values from the CTR (2.14×10^{-4} mSv/y). These AGED values for external terrestrial radiation were much lower than the global average of 0.48 mSv/y (UNSCEAR, 2000). The average H_{ex} for water samples was 6.14×10^{-3} in W2 ranging from 3.61×10^{-3} to 10.30×10^{-3} and a range from 3.54×10^{-3} to 8.62×10^{-3} in the MP with an average value of 5.36×10^{-3}. The average H_{in} in MP samples (average = 8.61×10^{-3}) revealed highest value of 14.35×10^{-3} and lowest value (5.46×10^{-3}) in the WA samples. The H_{in} revealed (average = 6.99×10^{-3}) having values ranging from 4.85×10^{-3} to 9.95×10^{-3} in W2. The calculated H_{ex} and H_{in} for all samples revealed values less than unity. The H_{in} and H_{ex} values for the MP, W1 and W2, on the other hand, were higher than the CTR values. This finding highlights the need for radiation safety precautions.

4.6.2 Annual Effective Doses

The annual effective dose trough the ingestion of water from the MP is presented in Table 15. The MP samples were used for this estimation because water from MPs were being used by residents for different uses. The overall annual effective dosage from natural radiation should not exceed 2.4 mSv/y (UNSCEAR, 2020). In this study, the total yearly effective dose equivalent owing to external terrestrial radiation and water consumption revealed an estimated value of 1.25×10^{-4} mSv/y which was lower than the allowed limit of 2.4 mSv/y. The value was likewise less than 1 mSv/y, which is the ICRP (2019) recommended limit for the members of the public. The WHO also recommends a maximum yearly effective dose of 0.10 mSv/y in drinking water (WHO, 2002, 2009). The MP value, on the other hand, was higher than the CTR value (0.89×10^{-4} mSv/y). Although the value from MPs was lower compared to the international limits, this study recommends the radiation control strategies at Rwamagasa ASGM. This is because, having a lower CTR value than values in MPs shows a gradual increase of the radionuclides in the MPs. These values must be controlled before reaching thresholds levels.

Table 15: Annual effective dose through ingestion of ^{238}U, ^{232}Th and ^{40}K in water samples

Category	Average activity concentration (Bq/L)			Average Annual Effective Dose (mSv/y)
MPs samples	^{238}U	^{232}Th	^{40}K	1.25×10^{-4}
	1.47 ± 0.13	0.41 ± 0.02	7.59 ± 0.68	
CTRs samples	^{238}U	^{232}Th	^{40}K	0.89×10^{-4}
	0.70 ± 0.02	0.43	2.99 ± 0.01	

4.7 Radon Concentration and its Health Hazards

The radon concentrations from selected points in CDs, Ds and MPs are shown in Table 16. Table 16 also includes computed values for the intakes and annual effective doses to which the public is exposed. The international limits for indoor radon according to the ICRP (2019) and (WHO, 2009) are 200 Bq/m^3 and 100 Bq/m^3, respectively. It is clearly seen from Table 16 that the average indoor radon concentrations from residences was 99.8 Bq/m^3, with the highest value (248.3 Bq/m^3) observed in D4. The results further showed that 70% of the dwellings had concentrations higher than the permissible amount of 100 Bq/m^3 (WHO, 2009). It had also been discovered that the average radon level in Ds is 6 times higher than in the CD (16.98 Bq/m^3). This high value in houses could indicate that people utilized mine tailings in the construction of their houses. Indoor radon concentrations in the dwellings ranged from 28.6 to 248.3 Bq/ m^3, compared to 11.4 to 27.5 Bq/ m^3 in the CD. In D, the yearly effective dose ranged from 0.58 to 5.01 mSv, with a mean value of 2.33 mSv. These dose values from Ds were greater than the CD results, which ranged from 0.23 to 0.55 mSv with an average of 0.34 mSv. The intakes followed the same pattern as the dose results. The acceptable average yearly effective dose from inhalation of radon and its decay products was 1.26 mSv (UNSCEAR, 2020). The WHO (2009) and (Stewart *et al.*, 2012) recommend the average dose limit of 1mSv/y for the public.

Table 16: **The radon concentrations (Bq/m3), Intake (Bq) and Dose (mS/y) from the dwellings of the control and mining areas**

Category	Sample ID	^{222}Rn Levels (Bq/m^3)	Intake (Bq)	Dose (mS/y)	Category	Sample ID	^{222}Rn Levels (Bq/m^3)	Intake (Bq)	Dose (mS/y)
	CD1	12.1±1.1	4.65	0.24		MP1	361.4±29.1	138.78	7.29
	CD2	27.5±2.3	10.56	0.55		MP2	120.3±10.3	46.20	2.43
Control	CD3	13.7±0.9	5.26	0.28		MP3	86.0±7.0	33.02	1.73
	CD4	11.4±0.8	4.38	0.23		MP4	286.2±25.3	109.90	5.77
	CD5	20.2±1.2	7.76	0.41	Mining Pits	MP5	85.1±8.6	32.68	1.72
	Average	16.98±0.7	6.52	0.34		MP6	234.3±22.1	89.97	4.72
	Minimum	11.4±1.7	4.38	0.23		MP7	185.9±13.8	71.39	3.75
	Maximum	27.5±2.4	10.56	0.55		MP8	198.4±16.0	76.19	3.99
	D1	78.3±6.9	30.07	1.58		MP9	224.7±19.8	86.28	4.53
	D2	57.6±4.8	22.12	1.16		MP10	118.4±9.8	45.47	2.39
	D3	123.6±10.2	47.46	2.49		Average	190.07±18.2	72.99	3.83
	D4	248.3±19.3	95.35	5.01		Minimum	85.1±7.9	7.79	0.41
Dwellings	D5	28.6±2.7	10.98	0.58		Maximum	361.4±35.2	138.78	7.29
	D6	179.8±16.0	69.04	3.62					
	D7	119.4±10.7	45.85	2.41					
	D8	107.6±11.0	41.32	2.17					
	D9	102.4±9.8	39.32	2.06					
	D10	112.7±10.2	43.28	2.27					
	Average	99.8±8.5	44.48	2.34					
	Minimum	28.6±2.2	22.12	0.58					
	Maximum	248.3±20.1	69.04	5.01					

*CD=Dwellings from the Control area, *D= Dwellings from mining area, *MP= Mining Pits

When radon levels in MPs were compared to those in Ds and CDs, the results showed that the MPs had higher levels. It is noted from Table 16 that the average radon concentration in MPs is 11 times higher than in CDs and approximately 2 times higher than in D. The maximum value of radon concentration was obtained in MP1(361.4 Bq/m^3). It is also noted that 40% of MP had values higher than the acceptable value of 200 Bq/m^3 (ICRP, 2019) and that 80% of MP had values higher than the recommended level of 100 Bq/m^3 (WHO, 2009). Higher levels of radon in the MP might be due to poor ventilation. These results highlight the need for the responsible authorities to survey the MP at the study area. The results further suggest the need for education for residents to construct houses with adequate ventilation and probably not to use soil taken from the MP for house construction.

Generally, Radon (^{222}Rn) is the direct outcome when ^{226}Ra atom disintegrates in the ^{238}U decay chain. Due to this fact, there is a relationship between levels of uranium and radon at a point (Moshupya *et al.*, 2019; Speelman *et al.*, 2006). This was evidenced in concentrations measured in in MPs, soil from the MPs and indoor radon results. The results of ^{238}U concentrations in MP (Fig. 21) and the levels of radon in Table 16 further proved this relationship. The highest levels of ^{238}U were recorded in the MPs, also the highest concentrations of ^{222}Rn in Table 16 are from the MP. This observation further proves the argument that, rocks in the pits may have significant contents of ^{238}U and the MPs were poorly ventilated. Also, higher levels of ^{222}Rn in dwellings in relation to the concentrations of ^{238}U from the MP suggest that residents might be using soil from the pits for houses construction.

4.8 Statistical Analysis

4.8.1 Descriptive Statistics

Table 17 (a) and (b) show statistical analysis for the total concentrations of trace and radioactive elements, respectively for samples from the mining pits, first and second washing areas. The results demonstrated that the radionuclide and trace elements concentrations had different statistical results, indicating that radionuclides and trace elements at the study area were not evenly distributed within the samples.

Table 17: (a) The Calculated Descriptive Statistics Value for the Trace Elements and (b) the Descriptive Values for the Radioactive Elements

(a)

Statistics	Cr	Co	Ni	Cu	Zn	As	Cd	Hg	Pb
Minimum	34.5	9.2	44.5	51.9	39.8	0	0	0	1.6
Maximum	280	38.7	138.4	737.7	215.4	60.5	14	3.72	34.2
Mean	73.7	19.6	85.0	156.2	121.2	14.1	4.8	1.1	9.4
SD	39.5	7.4	20.7	85.5	33.6	9.7	3.8	1.6	7.1
Variance	1562	55.0	429.4	7318.2	1128.4	93.8	14	2.7	50.8
Skewness	3.3	0.8	0.02	5.6	-0.3	2.5	0.1	0.9	1.7
Kurtosis	14.3	0.2	-0.1	38.6	0.2	9.4	-1	-1.1	3

(b)

	^{238}U	^{232}Th	^{40}K	RP	RD
Minimum	1.6	0.9	285.5	34.5	9.2
Maximum	95	96.2	1536	280	38.7
Mean	42.6	35.5	652.4	73.7	19.6
SD	23.5	29.5	219.9	39.5	7.4
Variance	554.	869.7	4835	1562	55.0
Skewness	0.7	0.95	2.4	3.3	0.8
Kurtosis	-0.5	-0.7	8.6	14.3	0.2

*SD is the Standard Deviation, RP and RD are the radon from the MPs and dwellings, respectively

Apart from the common statistics of minimum and maximum values, mean, standard deviation and variances, skewness is a measure of unevenness in statistical probability theory that represents the asymmetric nature of real random variables. The skewness of a normal distribution, in which data are symmetric around the mean, is zero. The results for the skewness in Table 17 showed varied amounts, this is because experimental data are not exactly symmetric in real life. Kurtosis, on the other hand is a measure of a distribution's relative peak or flatness as compared to a normal distribution. Only Zn was negatively skewed, whereas the rest elements were positively skewed. The Cu, Cr and As all had a high asymmetric nature. The Kurtosis linked with ^{40}K, Cr, Co, Cu, Zn, As and Pb was positive, indicating somewhat peaked distributions, whereas the Kurtosis associated with ^{238}U, ^{232}Th, Ni, Cd and Hg was negative, showing flat distributions, similar trends were shown by Ugbede *et al.* (2020).

A pie chart (Fig. 24) shows the percentage contribution of trace and radioactive elements in the study area. For the trace elements, Cu taken up 31.1% of the chart, followed by Zn (20.9%), Cr (18.8%), Ni (17.3%), Co (4.9%), As (3.2%), Pb (2.5%), Cd (1.3%) and Hg had a negligible percentage. Figure 24 indicates that Cu was dominant while Hg was the least dominant. Significant percentage of carcinogenic elements such as As, Cr, Ni and Pb indicates the likelihood for the carcinogenic effects to people working and living within the study area. The natural radioactive elements ^{40}K, ^{232}Th and ^{238}U showed varied contributions of 89.3%, 4.9% and 5.8%, respectively.

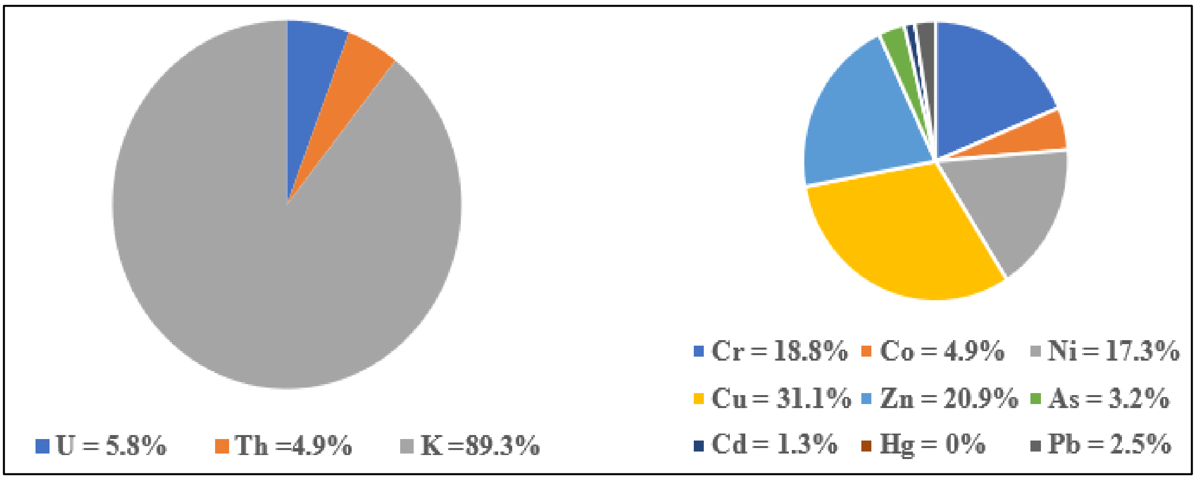


Figure 24: Percentage contribution for the radioactive materials (left) and for Trace Elements (right) from soil samples

4.8.2 Correlation Analysis

To explain the possible association elemental pairs, Pearson correlation coefficient was computed among elemental pairs with different R-values (Table 18). Using p-value less than 0.05, the correlation study produced 78 pairs of which 36 pairs were negatively and 42 of which are positively correlated. Negative correlation coefficient signifies negative linear relationship between pairs, whereas positive values indicate the opposite linear association. Correlation coefficient values above ±0.5 are considered significant. The highest correlation pair was ^{238}U/^{232}Th (r = 0.999) while the lowest correlation pair was ^{238}U/Cr (r = 0.054). The poor correlation indicates that there is no substantial relationship between the pairs. The ^{40}K was observed to have a strong correlation with all the trace elements expect for Zn ($r = 0.336$), this observation might be due to the high abundance of potassium in the study area (Fig. 23). the 62% of correlation pair were significantly ($r > 0.5$) greater than the 38% ($r < 0.5$), this observation suggest that many trace elements had the same anthropogenic sources (mining activities).

Table 18: Pearson Correlation Analysis for the Trace and Radioactive elements

	^{238}U	**^{232}Th**	**^{40}K**	**Cr**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Cd**	**Hg**	**Pb**
^{238}U	1											
^{232}Th	0.999	1										
^{40}K	-0.607	-0.624	1									
Cr	0.054	0.075	-0.826	1								
Co	-0.468	-0.487	0.986	-0.908	1							
Ni	0.572	0.590	-0.999	0.849	-0.993	1						
Cu	0.713	0.728	-0.989	0.739	-0.953	0.983	1					
Zn	0.545	0.527	0.336	-0.808	0.486	-0.375	-0.199	1				
As	-0.429	-0.449	0.978	-0.925	0.999	-0.986	-0.939	0.5232	1			
Cd	-0.335	-0.356	0.952	-0.959	0.989	-0.964	-0.899	0.607	0.995	1		
Hg	-0.429	-0.449	0.978	-0.925	0.999	-0.986	-0.939	0.523	1	0.995	1	
Pb	-0.220	-0.199	-0.642	0.962	-0.759	0.674	0.527	-0.938	-0.787	-0.845	-0.786	1

The positive correlation coefficient was absorbed between ^{238}U and ^{232}Th ($r = 0.999$). This means that the radionuclides in soil have a strong link. The high positive correlation coefficient observed between ^{238}U and ^{232}Th might be explained by the fact that uranium and thorium decay series occur collectively in nature. Comparable trend was verified by Özmen *et al.* (2004). As a result of this close association, the two radionuclides contribute to gamma radiation emission. The negative correlations of ^{238}U/^{40}K and ^{232}Th/^{40}K might be explained by the fact that ^{40}K does not come from the uranium decay series.

Significant negative correlation coefficient between radioactive elements uranium and thorium with potassium was seen to have almost same values of 0.607 and 0.624, respectively. Strong negative correlations were also observed between pairs Cr, Ni and Cu with K, also between Co, Zn, As, Hg, Cd with Cr. Ni, Cu and Pb revealed strong negative correlation with Co. It was further noted from Table 18 that As, Cd and Hg were strongly negative correlated with Ni whereas, As, Cd and Hg were negatively correlated with Cu. Similar observations were reported by Dugalica *et al.* (2010). The fact that the overall concentration of these metals to be easily available to vegetations entering complexes with humas can suggest insignificant associations (Dugalica *et al.*, 2010). The positive relationship among the pairs (Table 18) indicates same source of origin and their linearity is direct proportional. Largely, the correlation analysis revealed weak relationship and correlation between the radionuclides and trace elements.

The correlation between ^{222}Rn concentration in MPs and the levels of ^{238}U in the MP soil samples is presented in Fig. 25. The concentration of ^{238}U is reported elsewhere to contribute to the level of ^{222}Rn gas in MPs. There is evidence that support the concept of high soil gas ^{222}Rn in closed areas (Appleton, 2013; Baykara *et al.*, 2005; Ugbede *et al.*, 2020). The Pearson analysis (Fig. 24) showed a correlation (r = 0.6) at a 95% confidence level p-value (two tailed) = 0.06 for the concentration of ^{238}U and ^{222}Rn in MPs. The p-value greater than 0.05 might be attributed by the sampling variability and the spread of the data. However, high p-value does not mean the inequality of the groups or that there are no effects. The high p-value give the indication that the effect might be existing in a small quantity (Goodman, 2008; Halsey *et al.*, 2015; Sullivan & Feinn, 2012). It is clearly emphasized from the radiation protection standpoint that no any incremental level of radiation is not harmful to human health (UNSCEAR, 2020; WHO, 2009). It has also to be noted that radioactivity is site specific. This fact might contribute to high p-values because even areas which are very close to each other may have significant different levels of radioactivity. The ^{222}Rn levels in soil fluctuate depending on various factors such as soil water content, temperature, atmospheric pressure and soil texture (Amasi *et al.*, 2015).

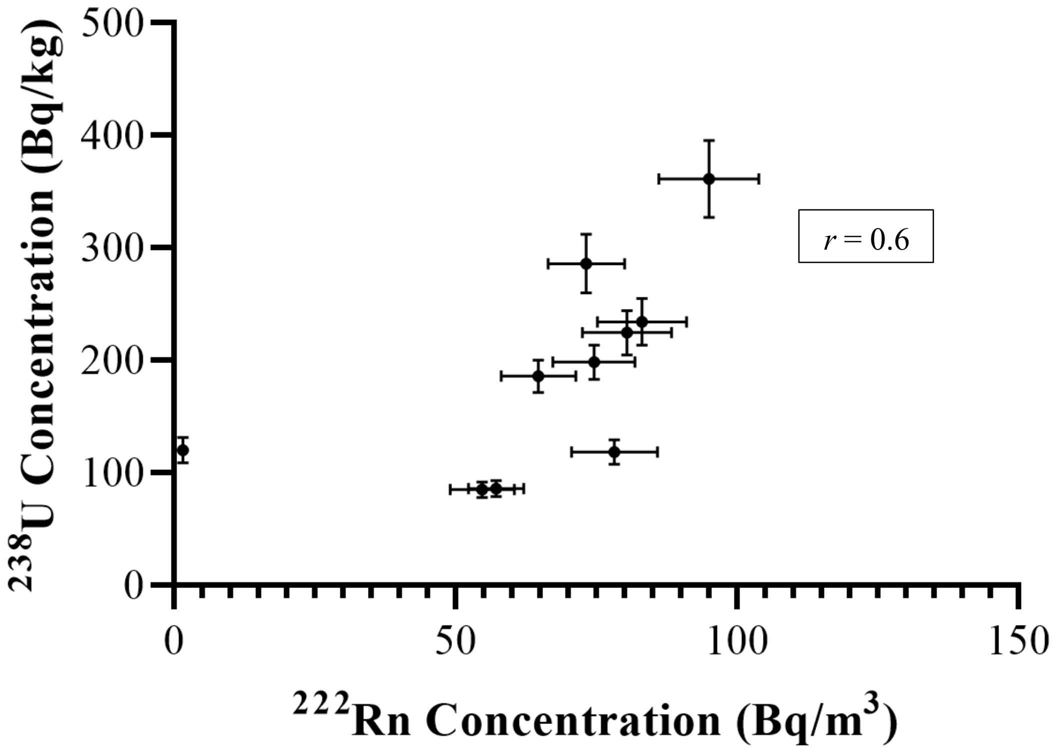


Figure 25: Relationship between uranium and radon concentrations for MPs samples

The field study observation revealed that some houses D1 to D10 (Table 16) were built using soils from the MPs (MP1 to MP 10). This claim was evidenced from residents at Rwamagasa ASGM. Residents further argued that the reason for using that soil from MPs is that the soil is wet enough to reduce the cost of water during construction and that soil was seen to have good characteristics according to their need. For this reason, the correlation between indoor radon concentration for houses (D1-D10) and the levels of uranium in soil sampled from MP1 to MP10 was determined (Fig. 26). It is clearly noted from Figure 18 that 40% (r = 0.4) supports the argument.

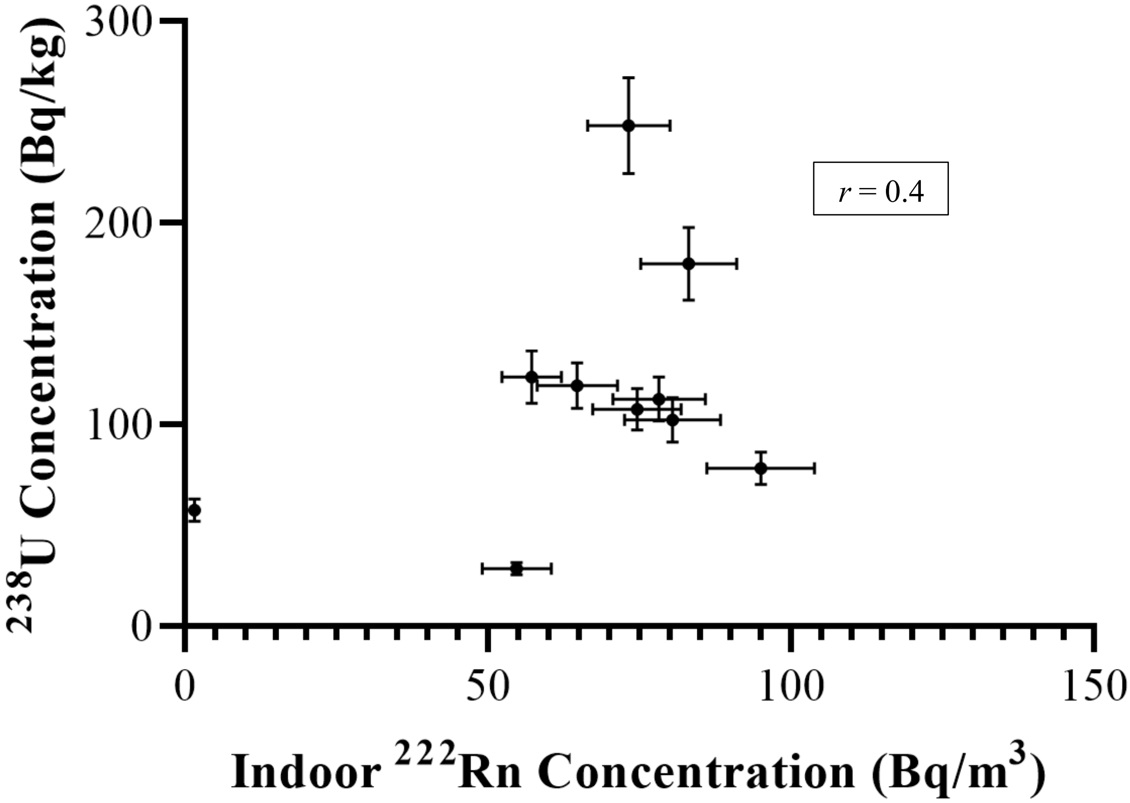


Figure 26: Relationship between uranium and indoor radon concentrations for soil samples from the mining pits and houses situated in the active mining area

This result shows moderate linear correlation between indoor ^{222}Rn gas concentration and mined soil which was claimed to be used in building construction. This observation suggests that probably the soil from the MPs were mix with other materials from elsewhere which reduced the levels of ^{238}U. However, it must be noted that not all ^{238}U that decay is converted to ^{222}Rn, there are other amount of ^{238}U that form other daughters in the series other than ^{222}Rn. Also, when ^{222}Rn decay, it is not necessarily found in the surrounding air. Other factors such as ventilation condition, cracks in the basement and walls (evidenced in houses at Rwamagasa ASGM), pore spaces, soil porosity, soil grain size and the amount of water in the soil influence the level of radon in air. Thus, the perfect relationship between ^{238}U decay and ^{222}Rn is not possible. Hence the correlation of 60% (Fig. 25) and 40% (Fig. 26) reveals a relationship between uranium decay and radon gas.

4.10 Artisanal and Small-scale Mining in Tanzania: A Policy Perspective

4.9.1 Artisanal and Small-scale Mining policymaking in Tanzania

The linkages the ASM sector has with the development of other social and economic sectors in Tanzania are intricately undeniable. The caution in the mineral policymaking in Tanzania is that issues related to the regulation and control of the adverse impacts of the ASM subsector are hardly addressed. Although the lack of participation can be blamed for poor ASM policymaking – there is a need for ASM policies in Tanzania to strike a balance with respect to environmental, social, and economic impacts of the ASM subsector.

The current policy making process in Tanzania follows a top-down approach starting from the ministerial level to the parliament for approval or disapproval. However, different scholars such as Mattee (2007) has suggested a model (Fig. 27) that intend to solve the problems facing a top-down approach.

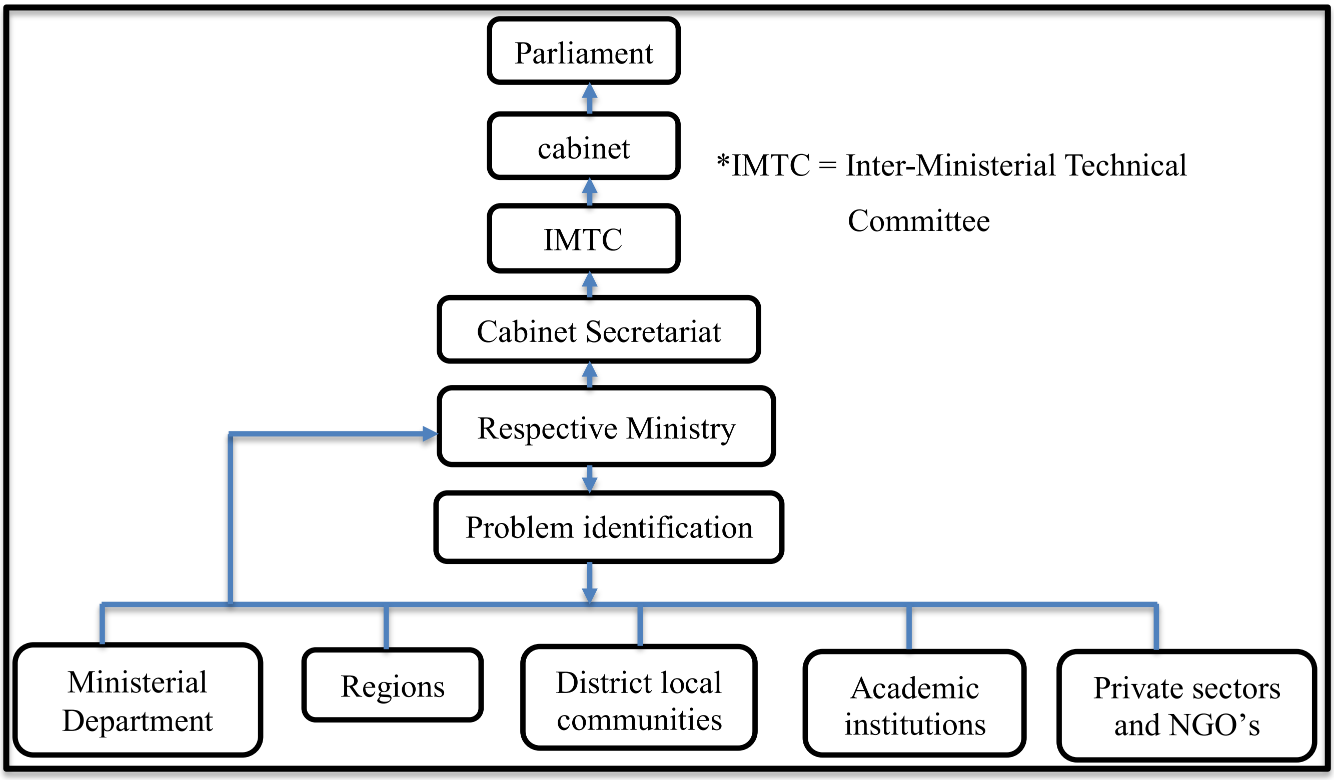


Figure 27: The policy making process in Tanzania (Mattee, 2007)

The model by Mattee (2007) still lack some aspects of inclusion. This study has come up with a model which allows many stakeholders to participate in the policymaking/amendment processes. In this case, the suggested policy cycle assessment (Fig. 28) would be a useful tool. If this cycle is clearly followed all scientific findings, community involvements, concepts and advice would be integrated in the formulation of policies (Giliberto & Andrea, 2020). However, for Tanzania, some policy aspects such as establishment of radiation control standards are not well stated. This is in part because Tanzania's approach to mineral policymaking has been tied up in adopting the standards set up by the international mining and mineral societies and organizations. Notice, however, that this approach does not give the possibility of including the in-country scientific findings and hence balancing the social and economic benefits against and environmental costs because international standards are developed based on missions that differ from the local settings. In principle, standards for NORMS are established based on the background of an area that is also influenced largely by the weather, climate, and geological characteristics of an area. The dependence on international standards in Tanzania has resulted to some conflicts because the standards used in the country's policies, laws, and regulations do not address control effects of additional backgrounds or incremental doses from NORMs. It is important, therefore, for the Tanzanian mine and mineral policies to be developed considering the local prevailing circumstances by using the now-available scientific evidence.

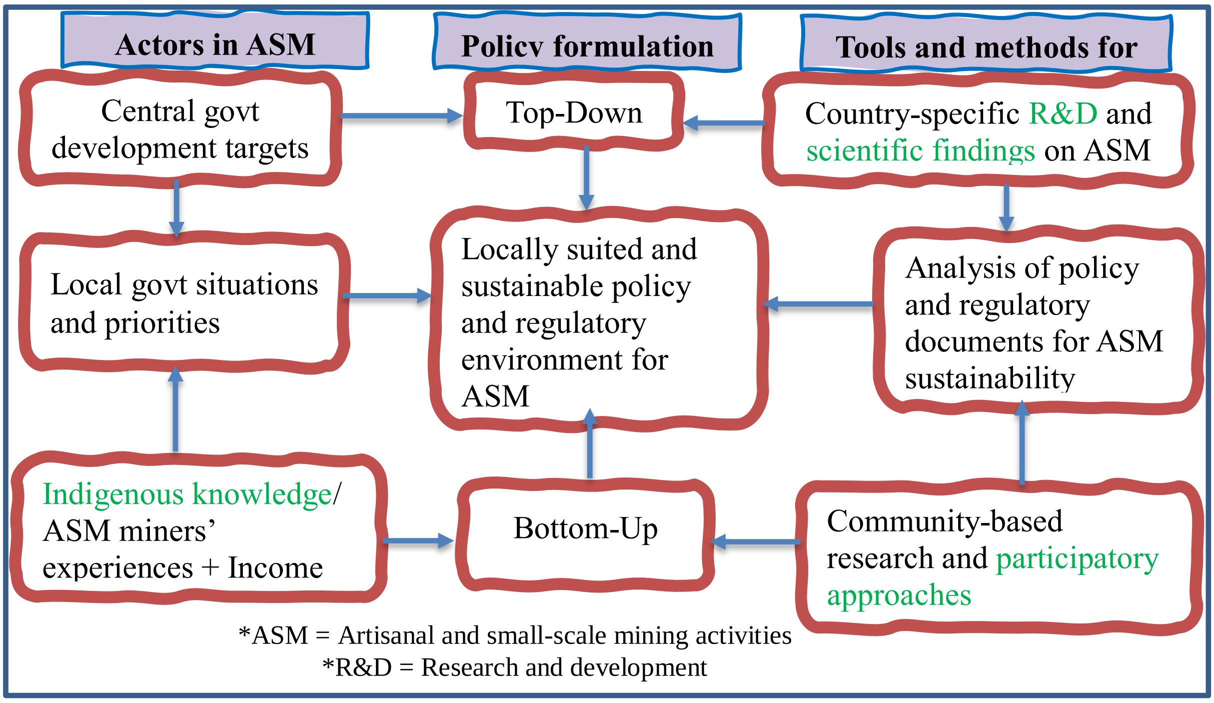


Figure 28: The suggested policy cycle framework

4.9.2 Impact Assessments and Policymaking

Some of the mining and mineral policies that Tanzania adopted or inherited from the colonial era, require that before commencing a mining project a thorough environmental impact assessment should be conducted. However, the actual implementation of this important guideline is somewhat questionable. For example, a study visit conducted in the Rwamagasa area found that, for NORMs and Heavy Metals (HM), baseline data of radioactive and heavy metals for most parts were either not available or not documented. This could probably mean that there were not enough previous studies for NORMs and HM for that specific local area. This could also be due to poor documentation of data from previous studies leading to lack of meaningful and consistent environmental datasets. The lack of well documented baseline information related to NORMs and HMs poses a challenge to the local-context policymaking for evaluation and standardization. Without consistent information it is also difficult to measure, quantify, and establish the human health risk for the ASGM/ ASM sector workers and the surrounding communities. As such, the lack of well-organized NORM and HM datasets makes it difficult for the Tanzania Government to make informed decisions pertaining to any environmental or public health endangering relating to mining activities.

4.9.3 Tanzania's Artisanal and Small-Scale Gold Mining Sector and International Regulations

The activities involved in long-term supervision, mining, processing, and recovery are subject to a diversity of national rules for the accountability of all parties involved and affected. Internationally, the perspective is that ASGM pollutes the environment, and the view is that ASGM should somehow be transformed for it to be sustainable. In this study, however, it is argued that ASGM may not be an environmental problem if mineral and mining policies are grassroot-based – to embrace the local on-the-ground conditions. This study argues that the small-scale/ artisanal miners and the Government should sit together to make miners oriented ASGM policy for the sector's sustainability. The marginalized, and sometimes, criminalized miners – their voices – need to be heard in the formulated policies. The global/ international "umbrella" policing for sustainable development e.g. 'Transforming our World' alone is not far-reaching enough (African Union, 2013).

In most developing countries of the Global South, Tanzania included, national economic growth policies privileges the multinational large-scale gold mining companies (African Union, 2013). The ASGM is largely excluded, isolated, at-risked, and regarded as enemies of environmental sustainability. However, it is important to note that, in some countries in the Global South, ASGM far exceeds large-scale industrial mining with respect to the size of the workforce, the amount of minerals produced, and the number of people/ 'beneficiaries' involved (African Union, 2013). In Ghana, for example, ASGM accounts for 30% of the total gold produced (Bansah *et al.,* 2018). This paper, therefore, proposes that Tanzania should develop its own regulatory framework of the ASGM sector, a framework that takes into consideration the livelihoods of the local people and environmental sustainability.

4.9.4 Status Quo Legislation and Amendments

The United Republic of Tanzania (URT) has indicated its intentions to formalize the ASGM sector albeit through state-led, top-down approaches (Kinyondo & Huggins, 2021). The efforts by Tanzania to formalize her ASGM sector are driven by the country's desire to fulfil the global sustainable development goals and to mitigate the negative environmental impacts caused by the mineral subsector. Because of the 'colonial' approaches that Tanzania is currently planning to use in reforming its mining and mineral sector, this paper predicts failure of the planned reformation rooted in the marginalization of the local community voices in the legislation making process. Since the Government of Tanzania has aimed at making the ASGM a national economy sector, it is imperative that the legislation-making process be participatory and highly inclusive (gender, small-scale miners, microcredit companies, traditional health practitioners, village communities, and local governance structures). A bottom-up approach to legislation making may abate legislation failure and exacerbation of rural poverty. Efforts such as granting mining rights, licensing of ASGM, and apportioning of concession quotas – to make ASGM taxable and a contributor to the state coffers should be done carefully. There is a danger that ASGM may fall into the hands of large-scale, highly mechanized, industrial mining companies – further exacerbating poverty and environmental degradation due to the formation of 'rebel miners' as part of the formalized ASGM (Gavin & Roy, 2009).

4.9.5 Scientific Findings and Community Participation

Scientific research findings are very important in policy development and improvement (Werner & Kai, 2017). New scientific outcomes play a significant role in nourishing existing policies and in forming new ones because they target emerging matters of policy relevance. Science needs to guide policymaking, giving methodological assistance to policy makers to smoothen the course of action. Likewise, scientific guidance may be required on an ad-hoc basis. Updated response may be given once wanted to help improve and preserve policies. Other main disputes in the monitoring process for public involvement involves three main factors, namely, the endorsement of rules for overall applicability, permitting of certain facilities, and improvement of post closure procedures for facility recovery and continuing supervision. Regarding endorsement of rules for overall applicability, the existing regulatory configuration needs that member of the community who are concerned in metal mining and processing in Tanzania be responsive of and reply to policymaking through their grassroot organizations (URT, 1997, 2008, 2009, 2010, 2010, 2011). The ministry responsible for mining and minerals could offer an online means for information gathering and organization that would aid the current and future national-level dialogues relevant to mining. The COVID-19 global pandemic has taught us the usefulness of online platforms. The Government of Tanzania needs to take advantage of such platforms that were strengthened in the pandemic. Currently, the ministry [in theory] has a strong approach to community involvement in licensing of metal processing facilities. The guidelines requires that the ministry do environmental assessments before-licensing and that community gatherings or hearings should be held in the neighborhood of the planned facility (URT, 2009, 2010, 2010).

4.9.6 Artisanal and Small-Scale Gold Mining: Environmental and Human Health Dimensions

Since the ASGM industry is a rapidly growing sector in Tanzania, it is important to focus on the safety and health of the environment and surrounding communities. The ASGM is a culprit when it comes to environmental and human health risk (Banzi *et al.*, 2000; Bose-O'Reilly *et al.*, 2009; Ikingura & Akagi, 1999; Ikingura *et al.*, 2006; Mwaipopo *et al.*, 2004; Rwiza *et al.*, 2016; Straaten, 2000). Environmental researchers, governments in the Global South, and large-scale mining companies all blame the ASGM for the deterioration of the environment and the potential for human health concerns. Unfortunately, the voices of the ‘ASGMers’ (those being blames) are usually never heard. The pollution and risk story are usually a one-sided story.

The human health risk is usually considered as biological, chemical, psychosocial, biomechanical, and physical. Researchers have pointed out risk of specific significance to susceptible subjects e.g. children and women to be of more importance to address. However, several of such risks could be attributed to factors e.g. absence of miner training about health threats; inadequate access to protective gears; and imperfect technical awareness due to inadequate practical training, little knowledge about radioactive sources and heavy metals or low literacy rates (Mwaipopo *et al.,* 2004). The ILO informs that approximately one million children aged between five and seven years are involved in ASGM and excavating actions globally (ILO, 2005).

In Tanzania, it is estimated that more than one million people are directly engaged in ASGM; of that, about 72.4% are children and men while 27.6% are women (Mutagwaba *et al.*, 2018). Furthermore, the reproductive wellbeing risks linked with ASGM involves intake or exposure to heavy and radioactive metals (Bose-O'Reilly *et al.*, 2009; Ikingura *et al.*, 2006; Straaten, 2000). Although a body of scientific evidence has revealed that the environmental and human health impacts related to the ASGM are real, in this study we argue that the introduction of more strict government instruments alone will not necessarily take away these problems. We suggest participatory approaches in institutionalizing/ formalizing the mineral sector and the ASGM subsector in particular.

4.9.7 Artisanal and Small-scale Mining or large-Scale Mining Companies?

The answer to the question posed above is not easy to arrive at. It is debatable whether, as a country, which mining sector between ASM and large-scale industrial mining is more sustainable. Large-scale mine operations are equally destructive. On the other hand, the ASM subsector is a vital basis for economic support of particularly in rural areas (Mwaipopo *et al.*, 2004). Despite the fact that the Tanzania Mineral Policy of 2009 powerfully stresses on the necessity to set out plans for justifying artisanal and small-scale mining into well thought-out and resourceful procedures in order to safeguard profitable employment and poverty lessening, it is still questionable whether the stipulated goals can be achieved. Whereas the Tanzania Government has made struggles to create an ASM unit in the organization structure of the Ministry of Minerals, there has been shortage of participatory legal and policy frameworks to upkeep and assist the sustainability of ASM in Tanzania. Stipulations in the country's Mining Act of 1998 and the Land Act of 1999 assert that all land in Tanzania is formally owned by the Government and that any transfer practice must stick to the laws of Tanzania. This poses a question of whether communities have the right to land and gives precedence to the government to allocate the land to whatever entity can afford the cost (Siri & Abel, 2016). We argue in this paper that this is the same colonial mentality—prohibiting the colonized from land, infrastructure, and property ownership.

One consequence of this has been to aggravate fissures between the large-scale and small-scale sectors, causing conflict over land and other fundamental livelihood resources. The necessity has hence arisen to formalize the ASM sector, including organizing and registering unregulated mining, taking the ASM into the formal economy. Besides, while large-scale mining and ASM are the two subsectors covered in the policy, the artisanal and small-scale mining subsector is being omitted in most cases. In light of this, even if the policy setting in the sector does not adequately addresses the requirements of all players in the sector, there some opportunities Tanzania can exploit to make sure that the sector turn into advantageous to all players sustainably.

4.9.8 Mining policies: Lessons from other Sub-Saharan Africa Countries

Like Tanzania, most of the sub-Saharan countries are also reliant on mineral resources (Fessehaie, 2018; Judith *et al.*, 2016). Although most of these nations have revealed unsatisfactory outcomes with respect to supportable use of resources, experience in other natural resource-rich nations e.g. Botswana has revealed that the mining sector can lead to sustainable socio-economic development. According to Lifuliro *et al.* (2018) some of the significant features underlying effective experiences in any investment take into account the active policy frameworks and implementation procedures. In Botswana, for instance, the mining policy has been branded by extraordinarily determined goals, intelligible design, and effective implementation scheme for the artisanal and small-scale miners. Whereas this is a superior know-how with respect to such nations, the circumstances are different in Tanzania, where the small-scale mining sector has been linked to aggravations in environmental and public health status (Bose-O'Reilly *et al.*, 2009; Ikingura *et al.*, 2006; Mutagwaba *et al.*, 2018; Mwaipopo *et al.*, 2004; Straaten, 2000).

In Mozambique, as per the size of the extractive industry extended, the nation has been involved in the solidification of the legal structures and monetary systems for the mining sector by increasing transparency in procedures and reporting (Chiziane *et al.*, 2015). For instance, in 2009, Mozambique applied to the extractive production transparency initiative and was acknowledged completely compliant to the Extractive Industries Transparency Initiative (EITI) guidelines in 2012. Mozambique also recognized the Global Partnership for Social Accountability in 2012, which intended to expand development outcomes by supporting improved legal resident involvement and response (IMF, 2008). As a result, Mozambique has been one among the fastest developing economies in sub-Saharan Africa over the last 25 years, with an average of yearly actual Gross Domestic Product (GDP) growth of 7.4% (World Bank, 2013). This solid performance was assisted by the determined application of credible macroeconomic guidelines and structural reforms, a promising external environment, donor funding and, in latest years, the discovery and utilization of natural resources. In this concern, Mozambique has been carrying out well on governance with upgrading in crucial areas such as government efficiency, regulatory excellence, and the rule of law (World Bank, 2013). It is evident that community participation, the rule of law, human rights, transparency, and democracy are intricately interlinked with sustainable development and efficient utilization of mineral resources.

For Namibia, the country's constitution requires that all natural resources belong to the government. The Namibia's Mineral Searching and Mining Act of 1992 offers that all rights and control over natural resources rest with the government (Annie, 2010). The Namibian government has established its mineral rule to guarantee growth of the mining sector. The policy is aimed at accruing interest equally from foreign and native investments in mining. According to the government policy, the government tries to find opportunities for the Namibians to profit from their nation's mineral resources and improve their socio-economic livelihoods (Annie, 2010).

It is commonly said that the Namibia's mining policy article is extraordinarily effective in its intent as it permits for better government involvement in mining production to protect straight profit from mineral production for the benefits of the Namibians. As the outcome, the Namibian mining division performance has been remarkable, recording a GDP share of 12% from mining by the year 2012 (World Bank, 2013). The condition in other nations such as Zambia, Ghana, and Botswana where the sector has been flourishing, local content guidelines have been established and executed with the objective of capturing more profits from the sector (Wilcox, 2015; World Bank, 2013). In line with the possible profits accumulated by the local people, it has been essential for the nations rich in mineral assets to embrace local content requirements in their policies and laws.

In contrast, for Tanzania, the impact of mining to the Gross Domestic Product (GDP) is still small when likened to Botswana and Namibia. The mining sector contribution to the GDP accounted for 3.7% in 2014, 4.0% in 2015, 4.8% in 2016, and 5.9% in 2019/2020 (BOT, 2018; URT, 2021). For Tanzania, there is thus a necessity to improve the situation regarding the involvement and active participation of citizens for the betterment of the ASGM sector and for poverty lessening. Incidentally, Botswana and Namibia are viewed as role models for sub-Saharan African nations as they have stretched their economic and social development by consolidating their mining and mineral sectors (Hoeffler, 2002).

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This work assessed trace and radioactive elements, radon gas and the mineral and mining policymaking process in the Tanzania mining industry. In addition to the discussions carried out, the following conclusions can be deduced from the present research.

For trace elements, the concentrations revealed a significant increase in the mining pits (MD), washing area A (WA), and washing area B (WB) samples compared to the control (C) samples. Also, some sampling points revealed average levels higher than the international tolerable limits. The results of the hazard indexes show that people living and working at Rwamagasa ASGM are at risk of carcinogenic and noncarcinogenic effects. The Hg revealed a much higher value in WB, which suggests that, probably, ASG miners at Rwamagasa use Hg during gold recovery. If this higher level of Hg in WB persists, acute health effects may occur at Rwamagasa in the near future. For radioactive elements, ^{238}U was observed to be dominant in MPs and ^{40}K was found to be high in all sampling areas. The correlation analysis between trace and radioactive elements showed a positive correlation of 62% and a negative correlation of 38%. The relationship between indoor ^{222}Rn, ^{222}Rn measured in the MPs and ^{238}U soil from the MPs revealed a linear relationship. Higher level of radionuclides and radon gas in the mining area than the control area calls for authorities and mining stakeholders to take remedial and precautionary measures to settle current trends.

The findings of this work showed further that, small-scale miners at Rwamagasa work in poorly ventilated areas. Furthermore, the results suggested that people use mine tailings to build their houses. Also, higher levels of ^{222}Rn gas measured in the MPs where miners spend more time might be adding more risk to mine workers. Higher values were detected in some houses built within the mining area. These levels and the radiological indices estimated were higher than the worldwide recommended values and values estimated from the control areas. Radon gas is associated with an increased probability of lung and other cancers.

In the second objective, the estimated hazard indices due to trace and radioactive elements revealed the possibility of residents and workers to have carcinogenic and non-carcinogenic effects. In some cases, children seem to be at higher risk than adults probably due to their behavior and lifestyle. The dermal pathway had a greater contribution to risk compared to the ingestion and inhalation pathways.

Furthermore, in the third objective, the Tanzania mining policy, laws, and legislations showed some aspects such as the establishment of radiation control standards that were not exhaustive. This is in part because Tanzania's approach to mineral policymaking has been anchored in adopting the standards set by the international mining and mineral societies and organizations. Notice, however, that this approach does not allow the possibility of including the in-country scientific findings and hence balancing the social and economic benefits against environmental costs. In principle, NORMS standards are established based on the background of an area that is also largely influenced by the weather, climate and geological characteristics of an area. The dependence on international standards in Tanzania has led to some conflicts because the standards used in the country's policies, laws and regulations do not address the control effects of additional background or incremental doses of NORM. Therefore, it is important to develop Tanzanian mine and mineral policies considering local prevailing circumstances using the now available scientific evidence. Also, Tanzania needs to have a policy cycle model that involve the participations of all stakeholders in the policymaking and amendments process. Relevant experts and scientific research input should be the focal point of the cycle.

Prior to this study, no studies had been carried out in the study area to evaluate the extent of the possible risk of radioactive and trace elements contaminants to the miners and the surrounding communities. Also, in the present study, a contribution of scientific research in the formulation of policy, law and regulations that includes the ASM/ASGM has been suggested. Previously, research was conducted on the effects of Hg on the environment and had largely excluded the radiological risk to human. Furthermore, none of the previous studies linked ASM/ASGM activities to mining and mineral and mineral sector policy making. This study brought in the confirmation that the mining policy in Tanzania slightly support the ASM/ASGM sub-sector, also the policy formulation processes exclude important aspects such as the inclusion of scientific findings and the involvement of scientists and other stake holders.

This study argued that studying the levels of trace and radioactive elements is not just enough. A detailed analysis of the radiological indices and importance of having strong policies, laws and legislations were assessed and documented. Noticeably, the future environmental and public health in the ASM/ASGM mining environment in terms of support, inclusion and involvement under the current Mining Policy necessitate replanning. These management strategies need to be integrated into and implemented in environmental and public health management plans to sustain the ASGM subsector.

5.2 Recommendations

Apart from the presented results and discussion, the present study recommends the following for achieving sustainable ASGM operations in Tanzania:

(i) The present study was only restricted to ^{222}Rn in MPs and dwellings, natural radionuclides and trace elements in soil and water. Because risk is additive, crops and other food products such as meat, milk and vegetables need to be investigated.

(ii) Issues surrounding exposure to ^{222}Rn, which is a toxic gas, must be urgently addressed and possible mitigation measures such as good ventilation in homesteads and mining pits must be insisted.

(iii) The present study recommends the inclusion of science and scientific findings in the policy cycle during the policymaking and policy review processes. The present study suggests that the current Tanzania Mining Policy be reviewed to include the important aspects of ASGM.

(iv) The government through its institutions should establish national radioactivity baselines, radioactive levels, and dose limits in soil, water and food basing on Tanzania backgrounds. Also, the government and mining stakeholders should see the need for giving health risk awareness regarding trace and radioactive elements to miners and the surrounding community at Rwamagasa ASGM.

(v) Samples acquired from human subjects would be extremely useful in a study including exposure and human health risk. Risk assessments based on blood, hair nails and other human samples would yield more precise results than those based solely on environmental samples. This study recommends more research basing on human subjects.

(vi) The studied ASGM is in Geita, which makes it a component of the Lake Victoria Gold Field (LVGF). This also forms the limitation of the study; more studies are recommended to focus on other ASGM to get the complete mapping throughout the region and other areas in Tanzania.

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APPENDICES

Appendix 1: Levels of trace elements in soil samples collected from a small-scale mine site at an area "A" dominated by mineral washing activities

Site ID	Location coordinate	Mean elemental concentration (±SD) (mg/kg)								
		Cr	Co	Ni	Cu	Zn	As	Cd	Hg	Pb
WA1	S03º06.181'E032º03.90'	73.48±2.01	20.32±2.29	70.61±3.95	146.18±1.11	104.55±1.14	14.71±0.76	0	0	11.39±0.90
WA2	S03º06.199'E032º03.894'	66.79±5.48	24.60±7.71	97.53±2.61	137.09±0.93	137.26±4.19	9.42±1.45	8.77±1.05	0	11.29±0.36
WA3	S03º06.189'E032º03.869'	60.63±3.83	21.5±3.54	90.48±1.04	127.15±2.20	130.54±4.28	9.91±0.33	7.58±1.43	0	9.42±0.19
WA4	S03º06.162'E032º03.854'	120.19±8.98	15.35±3.54	101.68±3.31	178.97±2.46	145.13±1.59	7.26±0.11	0	0	3.04±0.20
WA5	S03º06.178'E032º03.836'	90.48±3.34	15.65±0.90	81.64±0.81	129.88±1.65	98.28±1.67	20.46±0.77	0	0	10.27±0.82
WA6	S03º06.173'E032º03.845'	96.07±7.26	12.63±7.74	47.51±2.14	74.17±2.58	50.49±1.60	6.49±2.20	5.78±0.75	0	17.3±2.30
WA7	S03º06.203'E032º03.848'	49.39±4.91	14.76±1.60	98.23±6.30	130.98±1.71	145.75±6.84	15.16±0.69	0	0	3.27±0.25
WA8	S03º06.027'E032º03.870'	56.48±7.80	12.20±0.89	98.16±4.88	131.22±2.78	142.37±0.60	8.02±0.43	0	0	2.45±0.20
WA9	S03º06.049'E032º03.876'	72.01±7.45	18.11±1.85	97.91±1.57	162.85±3.55	128.62±2.14	24.09±1.35	0	0	10.89±0.98
WA10	S03º06.641'E032º03.861'	59.29±5.70	31.89±12.32	75.86±1.87	118.71±0.77	115.32±4.40	7.83±1.31	4.75±0.73	0	6.97±1.86
WA11	S03º06.031'E032º03.862'	109.08±1.90	28.69±1.63	80.11±2.50	183.00±7.08	105.53±2.13	21.74±1.71	0	0	24.44±1.63
WA12	S03º06.030'E032º03.844'	102.12±7.54	20.62±2.82	46.49±1.50	108.26±3.94	39.78±0.74	10.78±1.94	0	0	17.54±1.31
WA13	S03º06.019'E032º03.835'	67.19±6.17	24.9±1.40	102.34±2.55	191.24±2.83	125.42±4.47	2.67±0.08	7.3±0.73	0.05	10.67±1.21
WA14	S03º06.041'E032º03.812'	93.02±7.14	37.3±15.96	77.04±6.70	138.12±3.64	112.38±3.60	8.28±0.49	4.21±1.93	0	9.95±0.97
WA15	S03º06.057'E032º03.804'	69.64±14.88	38.73±12.19	82.57±9.42	154.79±4.12	122.31±2.90	10.1±0.52	5.83±1.55	0	9.03±0.17
WA16	S03º06.097'E032º03.764'	67.72±4.02	10.09±0.90	80.15±1.70	153.05±3.60	139.7±1.56	21.63±0.46	3.1±0.00	0	5.17±0.11
WA17	S03º06.994'E032º03.879'	55.99±1.87	12.7±1.54	95.94±3.73	128.21±3.16	138.19±2.19	10.74±1.48	0	0.053	4.45±0.30
WA18	S03º06.967'E032º03.845'	86.99±4.26	23.03±1.64	80.36±1.30	144.06±2.52	96.68±1.84	14.67±0.33	5.85±1.63	0	11.55±1.33
	Minimum	49.39±4.91	10.09±0.90	46.49±1.50	74.17±2.58	39.78±0.74	6.49±2.20	0		2.45±0.20
	Maximum	120.19±8.98	38.73±12.19	101.68±3.31	178.97±2.46	145.75±6.84	24.09±1.35	8.77±1.05		17.54±1.31
Overall mean for all sampling sites		77.59±5.81	21.284.14	83.59±3.21	140.99±2.81	115.46±2.66	12.44±0.91	6.34±1.16	0.05	9.95±0.84

Appendix 2: Levels of trace elements in soil samples collected from a small-scale mine site at an area "B" dominated by mineral washing activities

Site ID	Location coordinate	Mean elemental concentration (±SD) (mg/kg)								
		Cr	Co	Ni	Cu	Zn	As	Cd	Hg	Pb
WB1	S03º06.178' E032º03.904'	102.66±2.85	32.43±3.92	56.16±2.13	176.65±4.21	66.91±2.68	14.71±2.17	3.63±0.31	3.67	31.11±1.41
WB2	S03º06.198' E032º03.893'	69.87±0.70	21.95±9.61	52.26±2.69	98.04±4.62	73.77±6.23	8.17±1.29	6.11±2.34	3.59	10.63±1.41
WB3	S03º06.188' E032º03.858'	47.15±2.79	10.14±1.64	51.74±1.71	74.71±3.86	72.57±1.54	15.31±0.39	0	3.59	4.55±0.60
WB4	S03º06.162' E032º03.854'	52.73±3.73	28.54±3.66	53.29±4.85	85.78±6.85	70.03±3.97	8.28±1.20	7.25±1.36	3.71	9.23±1.23
WB5	S03º06.178' E032º03.836'	210.4±10.39	35.33±2.22	99.06±2.69	157.08±4.80	69.85±2.30	15.88±0.30	5.56±1.84	3.58	23.13±0.48
WB6	S03º06.173' E032º03.845'	280±12.45	15.5±0.97	69.82±3.20	230.66±3.99	88.89±1.62	44.13±0.79	2.26±0.00	3.62	10.67±0.48
WB7	S03º06.204' E032º03.847'	55.1±7.68	18.69±3.28	105.59±0.79	130.12±1.92	135.69±2.74	21.21±1.31	8.48±1.63	3.43	7.26±0.34
WB8	S03º06.029' E032º03.872'	93.96±5.31	26.08±4.26	62.52±2.49	146.32±3.88	84.58±1.94	21.4±1.21	6.83±2.37	3.55	26.04±0.82
WB9	S03º06.049' E032º03.873'	70.13±1.29	14.71±1.68	75.28±2.37	109.69±3.45	131.92±1.36	19.44±0.65	0	3.72	4.15±1.45
WB10	S03º06.641' E032º03.861'	114.03±14.47	18.31±8.13	70.23±3.30	155.61±3.55	85.65±0.39	60.54±1.16	0	3.61	14.36±0.91
WB11	S03º06.031' E032º03.862'	84.86±7.36	36.76±5.72	60.86±2.85	170.09±3.32	68.16±1.78	24.65±0.88	3.27±0.70	3.08	34.19±2.52
WB12	S03º06.030' E032º03.844'	66.39±1.62	10.73±0.81	69.23±3.80	118.75±1.71	94.05±1.82	16.22±0.89	0	3.68	9.65±0.50
WB13	S03º06.018' E032º03.836'	93.29±4.02	23.37±1.13	78.25±3.18	143.21±2.56	119.15±3.55	11.87±1.35	7.38±1.17	3.66	8.54±1.06
WB14	S03º06.041' E032º03.813'	87.27±4.57	21.01±2.00	92.63±4.92	159.95±0.85	142.82±1.14	25.07±1.64	0	3.28	10.31±0.85
WB15	S03º06.056' E032º03.804'	45.73±2.86	9.2±0.76	51.95±1.40	92.1±6.49	80.66±1.29	11.3±0.62	2.26±0.00	3.65	5.33±0.44
WB16	S03º06.097' E032º03.764'	61.43±1.75	17.52±2.15	96.08±3.86	155.33±2.88	157.85±3.63	11.91±0.49	2.08±0.00	3.7	5.99±0.10
WB17	S03º06.991' E032º03.880'	66.65±3.29	11.33±3.12	82.39±1.20	131.35±2.26	136.72±0.86	15.13±0.52	0	0.81	2.78±0.48
Minimum		45.73±2.86	9.2±0.76	51.74±1.71	74.71±3.86	66.91±2.68	8.17±1.29	0	0.81	2.78±0.48
Maximum		280±12.45	36.76±5.72	105.59±0.79	230.66±3.99	157.85±3.63	60.54±1.16	8.48±1.63	3.72	34.19±2.52
Overall mean for all sampling sites		94.23±5.13	20.68±3.24	72.19±2.79	137.38±3.60	98.78±2.29	20.31±0.99	6.98±0.34	3.41±0.69	12.82±0.89

Appendix 3: Levels of trace elements in soil samples collected from a control area, which had minimal mining activities

Site ID	Location coordinate	Mean elemental concentration (±SD) (mg/kg)								
		Cr	Co	Ni	Cu	Zn	As	Cd	Hg	Pb
C1	S03º06.490’ E032º03.160’	49.49±3.32	8.87±1.09	50.80±3.34	60.84±1.72	34.48±1.74	0.5	9.27±1.13	0	14.10±3.22
C2	S03º06.280’ E032º03.336’	53.01±3.56	30.21±2.63	85.78±6.09	141.16±3.84	160.75±3.19	0	6.86±1.84	0	12.79±2.32
C3	S03º06.225’ E032º03.372’	40.08±2.89	11.51±2.32	123.15±0.33	101.46±10.77	44.45±3.03	0.51	6.68±0.06	0	11.45±0.74
C4	S03º06.223’ E032º03.378’	56.57±4.72	24.80±4.09	79.70±7.60	113.96±9.87	82.79±3.32	0.514±0.056	7.04±1.90	0	12.40±2.32
C5	S03º06.229’ E032º03.370’	40.09±2.26	16.2±1.04	84.54±6.35	127.43±9.05	80.42±6.31	0.48	7.81±1.30	0	13.50±2.02
C6	S03º06.272’ E032º03.329’	49.6±2.34	15.9±2.80	92.98±3.12	122.3±7.21	83.86±4.78	0.49	8.17±0.90	0	16.00±1.98
C7	S03º06.298’ E032º03.360’	49.89±2.0	11.23±2.13	119.09±9.14	90.45±5.01	98.53±7.12	0.5	8.02±1.89	0	16.46±0.65
C8	S03º06.190’ E032º03.218’	51.98±3.98	27.8±4.21	50.81±2.52	87.47±5.09	36.52±12.10	0.41	7.03±0.81	0	16.10±0.98
C9	S03º03.218’ E032º03.207’	56.58±4.62	22.9±3.31	79.89±5.21	89.86±4.12	82.9±5.25	0.49±0.065	6.69±0.87	0	12.2±0.87
C10	S03º06.350’ E032º03.290’	50.87±3.08	19.09±1.98	81.89±7.68	108.43±6.32	111.54±8.62	0.47	7.13±0.11	0	12.00±1.32
	Minimum	40.09±2.26	8.87±1.09	50.81±2.52	60.84±1.72	34.48±1.74	0	6.86±1.84	0	11.45±0.74
	Maximum	56.58±4.62	30.21±2.63	123.15±0.33	141.16±3.84	160.75±3.19	0.514±0.056	9.27±1.13	0	16.46±0.65
Overall mean for all sampling sites		49.79±5.81	18.85±2.76	84.86±3.21	104.36±2.81	80.62±2.66	0.51±0.06	7.47±0.96	0	13.70±0.84

Appendix 4: Levels of Radioactive Materials in soil Collected from the Control, Mining Pits, and Washing Areas

Coordinates		Sample ID	^{238}U (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	Coordinate		Sample ID	^{238}U (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)
S03º06.490′	E032º03.160′	CTR-1	22.23±2.2	13.38±1.4	282.2±26.3	S03º06.181′	E032º03.904′	W1-1	32.54±2.9	12.70±1.3	887.5±89.2
S03º06.280′	E032º03.336′	CTR-2	12.32±1.1	6.40±0.5	26.8±2.5	S03º06.189′	E032º03.869′	W1-2	34.74±3.4	28.08±3.0	582.2±55.6
S03º06.225′	E032º03.372′	CTR-3	14.56±1.2	9.97±0.8	221.9±21.7	S03º06.203′	E032º03.848′	W1-3	33.32±3.3	21.36±1.9	564.0±53.1
S03º06.223′	E032º03.378′	CTR-4	9.29±0.7	20.21±1.9	256.6±26.1	S03º06.027′	E032º03.870′	W1-4	21.48±1.9	8.86±0.9	714.4±69.7
S03º06.229′	E032º03.370′	CTR-5	8.79±0.7	6.17±0.6	234.7±23.4	S03º06.641′	E032º03.861′	W1-5	29.66±3.1	16.98±1.7	554.0±54.9
S03º06.272′	E032º03.329′	CTR-6	12.25±0.9	3.61±0.4	320.9±30.8	S03º06.019′	E032º03.835′	W1-6	30.16±2.8	15.00±1.4	539.4±54.1
S03º06.298′	E032º03.360′	CTR-7	10.19±0.9	5.90±0.5	254.7±24.2	S03º06.041′	E032º03.812′	W1-7	21.48±1.8	13.30±1.2	704.6±70.5
S03º06.190′	E032º03.218′	CTR-8	15.27±1.5	4.97±0.5	306.4±30.8	S03º06.097′	E032º03.764′	W1-8	24.74±2.5	18.92±2.0	625.9±63.2
S03º06.420′	E032º03.207′	CTR-9	17.97±1.6	5.73±0.6	265.5±27.3	S03º06.967′	E032º03.845′	W1-9	32.74±3.5	16.74±1.7	626.7±61.9
S03º06.350′	E032º03.290′	CTR10	21.67±1.9	20.35±2.1	198.7±18.1	S03º06.020′	E032º03.897′	W1-10	30.74±2.9	14.94±1.3	595.4±60.2
S03º06.067′	E032º03.116′	MP-1	95.00±8.9	96.2±8.9	598.3±58.7	S03º06.178′	E032º03.9045′	W2-1	56.68±5.8	35.00±3.8	543.6±55.3
S03º06.076′	E032º03.983′	MP-2	1.56±0.1	0.96±0	597.4±60.0	S03º06.199′	E032º03.894′	W2-2	22.46±2.6	32.84±3.3	717.0±72.1
S03º06.070′	E032º03.969′	MP-3	57.20±4.9	70.8±6.9	809.8±79.2	S03º06.162′	E032º03.855′	W2-3	52.36±5.3	16.90±1.4	672.0±68.2
S03º06.062′	E032º03.867′	MP-4	73.24±6.8	80.5±7.5	463.5±42.6	S03º06.204′	E032º03.847′	W2-4	28.04±3.0	21.22±1.9	641.0±65.9
S03º06.080′	E032º03.921′	MP-5	54.72±5.7	74.94±8.1	564.7±55.1	S03º06.029′	E032º03.872′	W2-5	19.26±2.3	11.04±0.8	1535.7±120.7
S03º06.090′	E032º03.913′	MP-6	83.14±7.9	78.60±8.0	1070.7±106	S03º06.031′	E032º03.862′	W2-6	23.22±2.5	10.68±0.9	285.5±30.2
S03º06.098′	E032º03.902′	MP-7	64.74±6.6	54.34±4.9	480.2±47.9	S03º06.018′	E032º03.836′	W2-7	30.10±2.7	19.62±1.9	585.9±56.9
S03º06.188′	E032º03.693′	MP-8	74.60±7.3	82.02±7.9	514.2±52.4	S03º06.056′	E032º03.804′	W2-8	34.40±2.9	19.38±1.8	646.8±65.8
S03º06.221′	E032º03.653′	MP-9	80.44±7.9	94.62±8.6	461.9±43.6	S03º06.991′	E032º03.880′	W2-9	29.32±3.2	17.64±1.5	771.3±76.9
S03º06.210′	E032º03.680′	MP-10	78.24±7.6	64.68±7.1	687.4±69.6	S03º06.038′	E032º03.912′	W2-10	27.48±3.4	15.48±0.9	529.7±53.1

Appendix 5: Levels of Radon from the Mining Pits, Dwellings and Control Area

Coordinates		Sample ID	Levels (Bq/m^3)	Intake (Bq)	Dose (mS/y)	Coordinate		Sample ID	Levels (Bq/m^3)	Intake (Bq)	Dose (mS/y)
S03°06.352′	E032°03.293′	CD1	12.1±1.3	4.65	0.24	S03°06.076′	E032°03.116′	MP1	361.4±34.3	138.78	7.29
S03°06.423′	E032°03.208′	CD2	27.5±2.9	10.56	0.55	S03°06.076′	E032°03.983′	MP2	120.3±11.3	46.20	2.43
S03°06.191′	E032°03.219′	CD3	13.7±1.2	5.26	0.28	S03°06.070′	E032°03.969′	MP3	86.0±7.2	33.02	1.73
S03°06.296′	E032°03.362′	CD4	11.4±0.9	4.38	0.23	S03°06.062′	E032°03.867′	MP4	286.2±26.1	109.90	5.77
S03°06.270′	E032°03.330′	CD5	20.2±0.9	7.76	0.41	S03°06.080′	E032°03.921′	MP5	85.1±6.9	32.68	1.72
S03°06.103′	E032°03.939′	D1	78.3±8.0	30.07	1.58	S03°06.090′	E032°03.913′	MP6	234.3±20.7	89.97	4.72
S03°06.106′	E032°03.925′	D2	57.6±5.6	22.12	1.16	S03°06.098′	E032°03.902′	MP7	185.9±14.5	71.39	3.75
S03°06.112′	E032°03.941′	D3	123.6±13.0	47.46	2.49	S03°06.188′	E032°03.693′	MP8	198.4±15.2	76.19	3.99
S03°06.107′	E032°03.870′	D4	248.3±23.7	95.35	5.01	S03°06.221′	E032°03.653′	MP9	224.7±19.8	86.28	4.53
S03°06.101′	E032°03.952′	D5	28.6±3.1	10.98	0.58	S03°06.210′	E032°03.680′	MP10	118.4±10.9	45.47	2.39
S03°06.110′	E032°03.867′	D6	179.8±18.0	69.04	3.62						
S03°06.103′	E032°03.893′	D7	119.4±11.3	45.85	2.41						
S03°06.120′	E032°03.948′	D8	107.6±10.3	41.32	2.17						
S03°06.122′	E032°03.962′	D9	102.4±11.0	39.32	2.06						
S03°06.123′	E032°03.963′	D10	112.7±0.9	43.28	2.27						

*CD = Dwellings in the Control area, *D = Dwellings in the mining area, *MP = Mining Pits

Appendix 6: Levels of Radioactive Materials in water Collected from the Control, Mining Pits, and Washing Areas

Coordinates		Sample ID	^{40}K (Bq/L)	^{232}Th (Bq/L)	^{238}U (Bq/L)
S03°06.490′	E032°03.160′	C1	1.56±0.4	0.33±0.03	0.79±0.08
S03°06.280′	E032°03.336′	C2	1.31±0.2	0.35±0.02	0.71±0.05
S03°06.225′	E032°03.372′	C3	1.57±0.6	0.63±0.05	0.44±0.03
S03°06.223′	E032°03.378′	C4	5.75±0.7	0.41±0.04	0.83±0.04
S03°06.229′	E032°03.370′	C5	4.76±0.5	0.42±0.03	0.71±0.05
S03°06.076′	E032°03.116′	MP1	8.85±0.7	0.32±0.02	1.12±0.13
S03°06.076′	E032°03.983′	MP2	7.62±0.8	0.43±0.03	0.59±0.06
S03°06.070′	E032°03.969′	MP3	8.51±0.7	0.31±0.01	1.55±0.4
S03°06.062′	E032°03.867′	MP4	6.92±0.7	0.24±0.04	0.87±0.06
S03°06.080′	E032°03.921′	MP5	7.44±0.6	0.71±0.05	0.88±0.05
S03°06.090′	E032°03.913′	MP6	9.26±0.8	0.25±0.03	2.12±0.23
S03°06.098′	E032°03.902′	MP7	11.1±0.9	0.31±0.02	0.73±0.04
S03°06.188′	E032°03.693′	MP8	6.37±0.7	0.32±0.02	1.02±0.11
S03°06.221′	E032°03.653′	MP9	4.78±0.4	1.06±0.4	4.78±0.46
S03°06.210′	E032°03.680′	MP10	5.02±0.4	0.19±0.05	1.05±0.9

Coordinate		Sample ID	^{40}K (Bq/L)	^{232}Th (Bq/L)	^{238}U (Bq/L)
S03°06.181′	E032°03.904′	WA1	6.02±0.5	0.24±0.01	0.82±0.05
S03°06.199′	E032°03.894′	WA2	5.82±0.5	0.38±0.02	0.56±0.04
S03°06.189′	E032°03.869′	WA3	15.29±1.7	0.31±0.02	0.77±0.05
S03°06.162′	E032°03.855′	WA4	2.13±0.1	0.45±0.03	0.86±0.04
S03°06.178′	E032°03.836′	WA5	2.2±0.2	0.46±0.03	0.54±0.03
S03°06.183′	E032°03.901′	WA6	5.09±0.6	0.61±0.04	0.72±0.05
S03°06.027′	E032°03.870′	WA7	1.6±0.9	0.34±0.04	1.22±0.11
S03°06.049′	E032°03.876′	WA8	11.77±1.2	0.37±0.02	0.18±0.04
S03°06.641′	E032°03.861′	WA9	1.48±0.4	0.37±0.04	1.15±0.14
S03°06.019′	E032°03.835′	WA10	8.09±0.7	0.42±0.05	1.23±0.9
S03°06.178′	E032°03.895′	WB1	14.71±1.5	0.33±0.01	1.29±0.13
S03°06.198′	E032°03.893′	WB2	8.51±0.7	1.2±0.1	1.05±0.1
S03°06.162′	E032°03.854′	WB4	12.79±1.3	0.46±0.05	0.59±0.03
S03°06.173′	E032°03.845′	WB5	11.78±1.2	0.16±0.03	0.71±0.06
S03°06.204′	E032°03.847′	WB6	4.77±0.3	0.25±0.03	0.61±0.03
S03°06.029′	E032°03.872′	WB7	11.62±1.7	0.29±0.08	0.62±0.05
S03°06.049′	E032°03.873′	WB8	7.04±0.6	0.52±0.04	0.73±0.06
S03°06.030′	E032°03.844′	WB9	10.81±1.7	0.19±0.02	0.76±0.05
S03°06.031′	E032°03.862′	WB10	4.14±0.3	0.2±0.0	0.79±0.06
S03°06.178′	E032°03.895′	WB1	14.71±1.5	0.33±0.02	1.29±0.14

*C = Control area, *MP = Mining Pits, *WA = Washing Area A, *WB = Washing Area B

Appendix 7: Institutional Approvals

(a) Introduction letter for fieldworks

THE NELSON MANDELA
AFRICAN INSTITUTION OF SCIENCE AND TECHNOLOGY
(NM-AIST)

School of Materials Energy Water and Environmental Science

Direct Line: +255 272555070
Mobile Phone: +255756773286
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E-mail: revocatus.machunda@nm-aist.ac.tz

Tengeru
P.O. Box 447
Arusha, TANZANIA
Website: www.nm-aist.ac.tz

Ref No: NM-AIST/P010/T18

Date: 29th January, 2020

To Whom It May Concern

Dear sir/ Madam

RE: INTRODUCTION OF MR. ERASTO FOCUS

The aforementioned is a PhD student at our school of Material, Energy, Water and Environmental Sciences (MEWES) of the Nelson Mandela African Institution of Science and Technology (NM-AIST), specializing in Environmental Science and Engineering (EnSE).

This is to kindly let you know that, Mr. Erasto Focus is working on the research titled ***"Risk Assessment of Selected Radioactive and Trace Elements in Artisanal and Small-scale Mines"***.

I am therefore, kindly requesting assistance from your office for him to carry out his research activities in your area.

Please accord him any necessary assistance.

Yours Sincerely,

Dr. Revocatus Machunda
Dean-School of Material, Energy, Water and Environmental Sciences

(b) Approval of the use of field equipment

TANZANIA ATOMIC ENERGY COMMISSION

(Official Government body responsible for Atomic Energy Matters)

Telephone: +255 27 2970050/51/52/53
Celiphone: +255 754 361221 (DG)
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P.O. Box 743
ARUSHA
TANZANIA

AB.208/292/01/18.

31/03/2020

Erasto Focus
The NMAIST, School of MEWES,
P.O BOX 447, ARUSHA.

Dear Sir/Madam

Re: **REQUEST FOR ALFAGUARD RADON MONITOR EQUIPMENT**

Kindly refer to the above heading.

Please refer to you letter dated 30 March 2020 concerning the request for Alfa guard radon monitor equipment to be used for air sampling as per your research proposal. TAEC has been experiencing the problems developed on some equipment due to mishandling of the same during the use and improper operations. However, in recognition of importance of research and development initiatives the Director General of Tanzania Atomic Energy Commission accepted your request in condition that the equipment have to be operated by qualified staff with experience in operation of such equipment. TAEC has some personnel who can operates this kind of equipment and we will release him to be part of the mission and will be responsible for taking care of the equipment. If this is acceptable here then you have to meet some travelling costs and his per diems as per government circulars. If this plan is agreed then inform us for necessary arrangement.

Your sincerely

Yesaya Sungita
For Director General

Appendix 8: List of Plates

Plate 1: Laboratory survey with one of the supervisors, Dr. Firmi P. Banzi (right) taken at the Tanzania Atomic Energy Commission (TAEC) during a laboratory visit

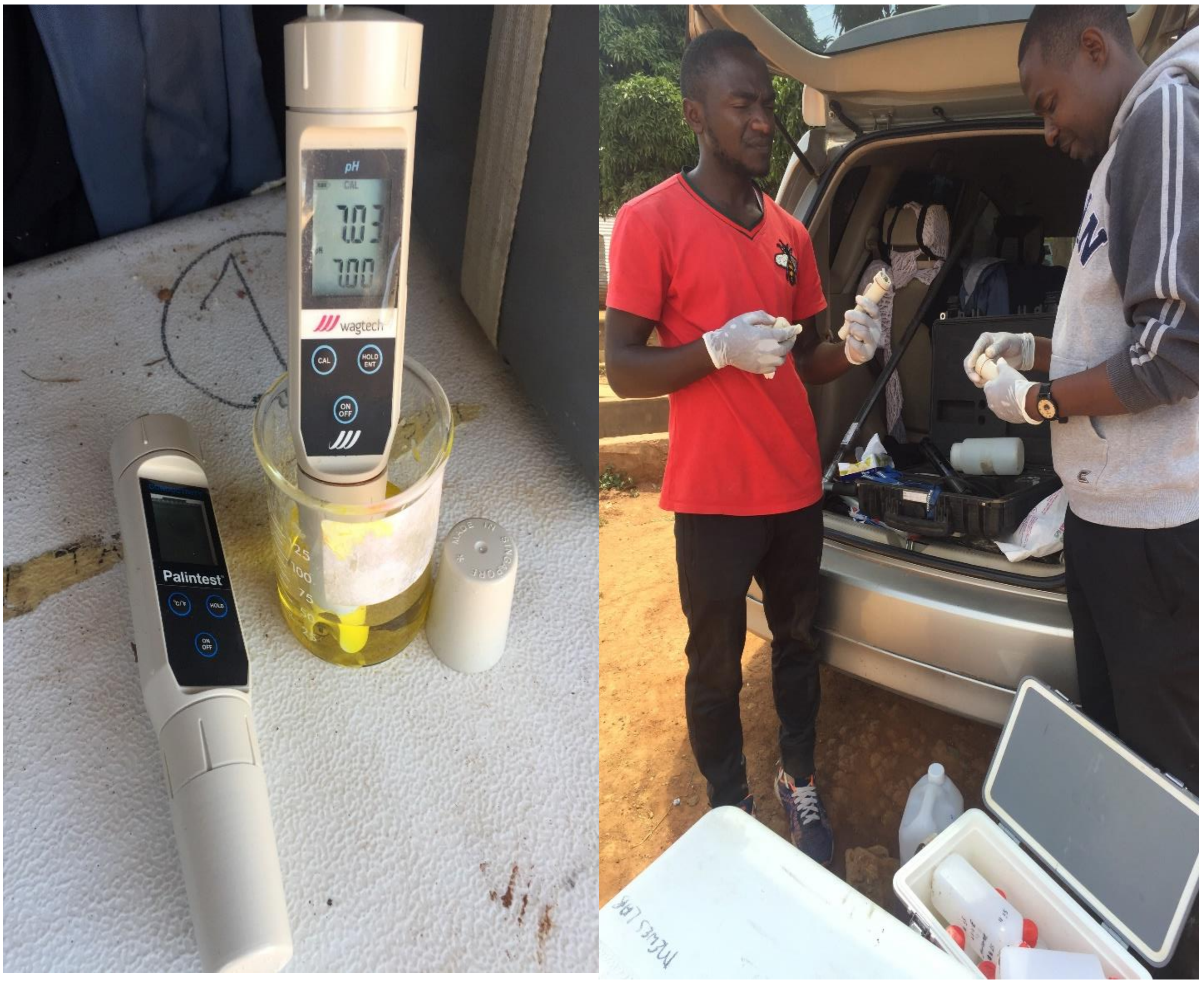

Plate 2: **Instrumentation step of this study, equipment calibration (left). On the right is the field and laboratory team getting ready for the field visit**

Plate 3: **Oven-drying of samples at the Nelson Mandela African Institution of Science and Technology (NM-AIST) Laboratory**

Plate 4: Soil analysis at the Nelson Mandela African Institution of Science and Technology (NM-AIST) Laboratory

Plate 5: Sample measurements at the Tanzania Atomic Energy Commission (TAEC) in the ED-XRF laboratory

Plate 6: Sample pulverization at the Tanzania Atomic Energy Commission (TAEC) Laboratory, Arusha, Tanzania

Plate 7: **Pelletizing of samples at the Tanzania Atomic Energy Commission (TAEC), Arusha, Tanzania**

Plate 8: **ED-XRF analysis for soil samples at the Tanzania Atomic Energy Commission (TAEC), Arusha, Tanzania**

Plate 9: *S*ample analysis ongoing in the HPGe laboratory

Plate 10: Sample placement to the HPGe detector

Plate 11: A pre-sampling set up and calibration of the field equipment

Plate 12: The main researcher (middle) with field assistants during sampling

Plate 13: **Typical working environment characteristics of the ASGM subsector of Tanzania**

Plate 14: Washing of the mined materials for gold recovery ongoing at one of the sites

Plate 15: A barehanded miner grinding the mineral materials at one of the visited study sites

Plate 16: A makeshift crushing machine operating at one of the study sites

RESEARCH OUTPUTS

(i) Publications

Focus, E., Rwiza, M., J., Mohammed, N., K., & Banzi, F., P. (2021). Health Risk Assessment of Trace Elements in Soil for People Living and Working in a Mining Area. *Journal of Environmental and Public Health*, 2021, 1-10. https://doi.org/10.1155/2021/9976048

Focus, E., Rwiza, M., J., Mohammed, N., K., & Banzi, F., P. (2021). The influence of gold mining on radioactivity of miming sites soil in Tanzania. *International Journal of Environmental Quality*, 46-47 (2021-2022), 147-162 https://doi.org/10.6092/issn.2281-4485/13288

(ii) Submitted manuscript

"Artisanal and small-scale mining in Tanzania and health implications: A policy perspective", *Environmental Science and Policy*; Elsevier (**Under review**).

(iii) Poster presentation