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**ASSESSMENT OF RADIONUCLIDE LEVELS IN SOIL, WATER, AND
FOODSTUFFS FROM SELECTED GOLD MINING AREAS IN UGANDA**

BY

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DECLARATION

I, Patience Natumanya, hereby declare that the research dissertation titled "Assessment of radionuclide levels in soil, water, and foodstuffs from selected gold mining areas in Uganda" is my original work and has never been submitted, in whole or in part, to any other institution or university for any academic award.

I further declare that all sources of information and references used in this dissertation have been duly acknowledged and cited. Any assistance or contributions received during this research have been explicitly stated.

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APPROVAL

This dissertation, entitled: "Assessment of radionuclide levels in soil, water, and foodstuffs from selected gold mining areas in Uganda" submitted by Patience Natumanya in partial fulfillment of the requirements for the award of the degree of Master of Science in Chemistry of Makerere University, has been examined and approved.

We hereby certify that this dissertation conforms to the required academic requirements and is adequate in scope and quality for the award of the specified degree.

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DEDICATION

This dissertation is dedicated to my beloved family, whose unwavering support, encouragement, and sacrifices have been the foundation of my academic journey. I also dedicate this work to my parents, for instilling in me the values of hard work and perseverance, and to my siblings, for their constant inspiration and understanding throughout this endeavor. I also dedicate this work to the communities living in gold mining areas of Uganda, whose resilience and experiences continue to inspire the pursuit of knowledge for a safer and healthier environment.

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LIST OF ABBREVIATIONS

μSv	Microsievert
^{232}Th	Thorium-232
^{238}U	Uranium-238
^{40}K	Potassium-40
AED	Annual Effective Dose
D	Absorbed dose
DCF	Dose Conversion Factor
DNA	Deoxyribonucleic Acid
ELCR	Excess Lifetime Cancer Risk
Hex	External Hazard Index
Hin	Internal Hazard Index
IAEA	International Atomic Energy Agency
IAED	Indoor Annual Effective Dose
ICP	Inductively Coupled Plasma
ICPR	International Commission on Radiological Protection
mSv	Millisievert
NDP	National Development Plan
nGy	Nanogray
NORMS	Naturally Occurring Radionuclide Materials
OEAD	Outdoor Annual Effective Dose
SDG	Sustainable Development Goal
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organisation

ABSTRACT

This study assessed the levels of naturally occurring radioactive materials in soil, sediments, water and selected foodstuffs from artisanal and small-scale gold mining areas in Uganda, where local communities may be exposed to radionuclides, by measuring in-situ radiation dose rates using a portable Geiger counter and determining the activity concentrations of ^{238}U , ^{232}Th and ^{40}K in collected environmental samples through Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The results obtained showed that the average radioactivity levels for soil and sediment samples ranged from 0.057 to 0.102 Bqkg^{-1} for ^{238}U , 0.012 to 0.278 Bqkg^{-1} for ^{232}Th , and 5.2E-06 to 8.5E-06 Bqkg^{-1} for ^{40}K . These values were all below the world average values of 33 Bqkg^{-1} , 45 Bqkg^{-1} and 420 Bqkg^{-1} for ^{238}U , ^{232}Th and ^{40}K respectively. The average radioactivity levels in cassava tubers for ^{238}U were 0.019 Bqkg^{-1} , 0.0113 Bqkg^{-1} , 0.0102 Bqkg^{-1} , those of ^{232}Th were 0.038 Bqkg^{-1} , 0.037 Bqkg^{-1} and 0.039 Bqkg^{-1} while those of ^{40}K were 8.9E-05 Bqkg^{-1} , 8.1E-05 Bqkg^{-1} and 8.7E-05 Bqkg^{-1} respectively for Namayingo, Kassanda gold mining areas. These values were all below the world average values of 35 Bqkg^{-1} , 30 Bqkg^{-1} and 400 Bqkg^{-1} for ^{238}U , ^{232}Th and ^{40}K respectively. Whereas tea samples from Buhweju indicated ranges of 0.012 to 0.015 Bqkg^{-1} , 0.035 to 0.037 Bqkg^{-1} , 3.66E-09 to 9.27E-05 Bqkg^{-1} for U, Th, K respectively. The annual effective dose of exposure by oral ingestion of cassava tubers and tea for adults with the mean values were approximately 0.0011 mSvy^{-1} far lower than the recommended safe limits of 1 mSvy^{-1} and also lower than the world average ingestion dose of 0.3 mSvy^{-1} . The calculated average annual effective dose due to the ingestion of water was approximately 0.0018 mSvy^{-1} which was below the world average annual effective dose from ingestion of NORMs of approximately 0.002 mSvy^{-1} . The excess life cancer risk (ELCR) was lower than their corresponding permissible values of 0.29×10^{-3} . All average values were below international limits, indicating no significant health hazards for the local population. The study reveals that there are currently no potential health risks associated with the consumption of water and foodstuff from gold mining areas studied.

Keywords; ICP-MS, radioactivity levels, annual effective dose and excess life cancer risk

CHAPTER ONE: INTRODUCTION

1.1 Background

Radionuclides are elements that release ionizing radiation, which destroys DNA, raises cancer risks, damages organs and tissues, and toxifies the ecosystems (Asere & Ajayi, 2015). They are naturally occurring or man-made substances emitting radiation during their decay (IAEA, 2016) and are not stable due to the excessive charge concentrated at the nucleus, and as such, they undergo radioactive decay to attain stability (Moshupya et al., 2022). Radioactive decay, or radioactivity, is the spontaneous disintegration of the nucleus of an atom of an element as it emits alpha, beta, or gamma rays or a combination and releases energy (Touranlou et al., 2024). In the earth's crust, the decay of ^{238}U , ^{232}Th , and ^{40}K releases γ -rays and energetic particles called α -particles and β -particles (Gulu et al., 2023). Alpha particles are produced when the nucleus of an unstable atom loses two protons and two neutrons (He nucleus), while beta radiation occurs when a nucleus of an unstable atom loses either a positron or an electron (Madzivire et al., 2013). Gamma radiation is produced when the nucleus remains in an excited state after alpha or beta decay releases excess energy to attain a stable state. Alpha particles are positively charged, and beta particles can be either positive (positron) or negative (electron) while gamma particles are neutral (Focus et al., 2021).

The earth's crust contains various concentrations of the above long lived naturally occurring materials whose potential harmfulness depends on their half-lives and chemical behavior including Uranium (^{238}U , $T_{1/2} = 4.47 \times 10^9$ years), thorium (^{232}Th , $T_{1/2} = 14.05 \times 10^9$ years), and potassium (^{40}K , $T_{1/2} = 1.25 \times 10^9$ years) (Amin & Ahmed, 2013), basing on the origin and type of rock (Mwalongo et al., 2023). They are found naturally in the Earth's crust and can be released into the environment due to human activities that can emit radiation like mining, handling, processing, and storing radioactive waste, as well as using radioactive materials and radiation in research and medicine (e.g., X-rays, CT scans, and radiotherapy) (Odelami et al., (2024). Additionally, they are a source of low-dose environmental radiation (Tripathi et al., 2019). Even low-dose radiation exposure is linked to a number of harmful health outcomes, including teratogenesis, eye abnormalities, cardiovascular and cerebrovascular diseases, psychological disorders, and malignancies (Niedzwiecki et al., 2019).

Uranium and Thorium can be unintentionally brought to the surface from gold mining processes, potentially contaminating plants and entering the food chain, which poses radiological risks to the public (Winde et al., 2019). Hence geological materials, primarily rocks and soil, naturally contain ^{232}Th and ^{238}U series as well as natural ^{40}K that result into natural radioactivity (Akpanowo et al., 2020). Due to their large ion radius, ^{238}U and ^{232}Th may be particularly concentrated in late crystallizing rocks like granites and other alkaline magmatic ores, which are frequently accompanied by other incompatible elements like Rare Earth Elements (REE) (Arogunjo et al., 2009). The average activities of these elements in the undifferentiated earth crust are between 25 to 50 Bqkg^{-1} (UNSCEAR, 2000). Both uranium and thorium present health risks due to their accumulation in human tissues, with uranium being both radiotoxic and chemically toxic (Oeh et al., 2007), while thorium should only be regarded as radiotoxic (Amin & Ahmed, 2013, and Khan et al., 2020). These radionuclides pose health risks because of their propensity to accumulate in human tissues.

Uranium (U) is a dense element found in low concentrations in rocks, soil, and water, typically at 2 to 4 parts per million in Earth's crust (Harmsen & Haan, 1980). It primarily exists in mineral forms like uraninite and contributes to Earth's internal heat through radioactive decay (Moshupya et al., 2022), with the average concentration in the earth crust is 2.8 mgkg^{-1} (McLennan, 1998). Uranium is present in various minerals, including oxides and silicates (Smičiklas & Šljivić-Ivanović, 2016). In contrast, Thorium (Th), which is more abundant with an average concentration of 8 to 12 parts per million, mainly occurs as isotope ^{232}Th in oxide minerals like monazite and also contributes to internal heat and natural radioactivity (Rabuku & Malik, 2020). Thorium's decay also contributes significantly to Earth's internal heat and natural radioactivity.

On the other hand, Potassium is a key component of many minerals that compose rocks and the eighth most abundant chemical element in the crust of the Earth. The radioactive isotope ^{40}K undergoes electron capture and potentially β^+ decay to ^{40}Ar and β^- decay to ^{40}Ca . One of the most popular geochronological methods is the decay of ^{40}K to ^{40}Ar (Naumenko et al., 2013). Potassium (K-40) is a major contributor to natural radioactivity present in soils and rocks and is usually measured as a percentage of total potassium in geological materials. Since potassium is a micronutrient, it stands to reason that certain properties of the soil would encourage its mobilization and subsequent uptake by the plant (Pietrzak-Flis et al., 2001). However, ^{40}K is a

necessary biological element, and human tissue's concentration in it's strongly controlled by metabolism (C. Ononugbo et al., 2017). These NORMs can be released into the environment through mining activities and ore processing resulting in possible air, water, and soil contamination.

Natural radioactivity is the primary source of radiation dose received by the general population (UNSCEAR, 2000). Among natural radionuclides, external gamma radiation exposures are mostly caused by ^{40}K , ^{232}Th , and ^{238}U and their respective decay products, especially ^{226}Ra and its subsequent decay products, are the main sources of internal exposure to NORMs (Faanu et al., 2024). The assessment of internal radiation dangers, such as cancer, to the population depends critically on the determination of NORM activity concentrations in foods and the radiological effects of consuming such foods, especially in gold mining using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Balaram, 2021). The concentrations of these radionuclides in soil and rock vary significantly depending on local geology and geographical characteristics (Ugbede & Echeweozo, 2017 and Habakwiha et al., 2023). NORMs are present throughout the environment and contribute to natural background radiation originating from sources such as the Earth's crust, water, air, the human body, and cosmic rays (Nabayaogo et al., 2022). Their distribution is strongly influenced by the geological composition of specific areas particularly the type of rock resulting in spatial variations in natural radioactivity levels across different locations (Silver et al., 2016). In addition to natural factors, anthropogenic activities such as mining, mineral extraction, and processing can significantly elevate concentrations of these radionuclides in the environment (Faanu et al., 2024), thereby increasing the potential radiological risks to ecosystems and human populations.

The most important NORMs in radiation protection are ^{238}U , ^{232}Th decay series, and ^{40}K (Odelami et al., 2024) and are regarded as dangerous for public health if consumed in relatively high concentrations (Yarima et al., 2019). Although radioactive decay naturally produces radionuclides in rocks and soils, mineral extraction and processing are primarily responsible for the environmental phenomena linked to radioactive contamination (Perevoshchikov et al., 2022). Even low levels of these elements can pose serious health risks including neurological disorders, cancer, DNA damage, genetic mutations, organ and tissue damage and immune system suppression if they enter the human food (IAEA, 2016; Francisca et al., 2023 and Odelami et al.,

2024). In light of the numerous factors, it is thought to be crucial to examine the existence of radioactive material in foods, especially staple foods, since this could have an impact on people in the artisanal and small-scale gold mining area (Hassan et al., 2021a).

Artisanal and small-scale gold mining (ASGM) is a significant economic activity in Uganda, but it is also associated with environmental challenges, including the potential increase of NORMs in soils and water. During mining and ore processing, radionuclides such as ^{238}U , ^{232}Th , and ^{40}K can be redistributed and accumulate in the environment, posing possible radiological risks to miners and nearby communities (Focus et al., 2021b). Furthermore, during the field study, it was observed that farmers often use these wastes, also known as tailings, for construction and agricultural purposes as soils and significant volumes of contaminated wastewater are directly released into the environment, polluting wetlands, surface water and subterranean water. In addition, these materials weather down and erode, forming sediments that settle in rivers, lakes, oceans, and wetlands, affecting the environment and social systems (Turyahabwa et al., 2024). In the regions where the mines are located, the ecology and local population have suffered greatly as a result of mining operations that produce radiation (Orosun et al., 2022).

Radioactivity in different materials like rocks, soils, sediments, water, foodstuff, ceramics from worldwide has been studied by distinct authors including Khisa Wanyama, et al., (2020), Atibu et al., (2022), Moshupya et al., (2022), Yang et al., (2023) in gold mining areas. According to previous study conducted in Uganda by Silver et al., (2016), soils and mine tailings from gold mining in southwestern Uganda regions contain higher active concentrations of these radionuclides, often above world average levels. This suggests increased background radiation and related health hazards. Measurements in Southwestern Uganda, for example, revealed activity concentrations of ^{238}U , ^{232}Th , and ^{40}K that varied greatly but were frequently higher than global averages (Silver et al., 2016). This requires ongoing monitoring and radiological risk assessment are necessary to protect miners and communities from radiation exposure. This concern is further amplified by the widespread nature of ASGM in Uganda.

In Uganda, ASGM is widespread and often operates without strict environmental oversight; the use of rudimentary techniques and improper waste disposal practices in such operations can significantly worsen the dispersion of radionuclides within the ecosystem. Despite the growing attention to mining related pollution, limited research has been done to address the environmental

challenges and evaluate radiological impacts in Uganda's gold mining areas, particularly concerning chronic exposure through ingestion and direct environmental contact. In the selected gold mining areas for this study, farmers grow food crops like cassava, maize, beans, banana, tea, coffee and millet in the open spaces and irrigate their farms with contaminated water (mining discharges) which results into food contamination through soil-plant transfer. The quality and safety of the food produced may be negatively impacted if the agricultural soil and water become contaminated by natural radionuclides and heavy metals that are absorbed from the disposal of trash, sludge, wastewater, and dust from mining sites.

There have been some health and environmental impacts linked to the use of primitive mining and mineral processing techniques as well as a seeming lack of awareness of the risks involved (Akpanowo et al., 2020), which poses health risk to the environment and communities. In Uganda, there is limited scientific data for NORMs in soil, water and foodstuffs which makes it challenging to assess the potential risks and develop effective interventions. This study, therefore, aims to address this knowledge gap by determining the radioactivity levels in soil, water, and foodstuffs from selected gold mining areas using inductively coupled plasma mass spectrometry (ICP-MS). Foodstuffs (mainly staple crops) grown in proximity to mining activities were analysed together with soil and water from the region.

1.2 Problem statement

Artisanal and small-scale gold mining in Uganda is a significant economic activity, but its informal extraction and processing can generate enormous waste containing long-lived naturally occurring radionuclides, which can lead to numerous environmental hazards, including contamination of soil, water, and food chain, radiation exposure and health concerns like DNA, organ, tissue damage and cancer risks, ecological effects, due to high levels of radionuclides in the environment. While ASGM is suspected to mobilize naturally occurring radionuclide materials (NORMs), there is limited quantitative data on radionuclide levels in environmental samples from gold mining areas in Uganda. Therefore, the purpose of this study was to determine the levels of naturally occurring radioactive materials in food, water, and soil from a chosen Ugandan gold mining region and to determine the health risks associated with the pollution.

1.3 Objectives of the study

1.3.1 General objective

To assess the levels and health risks of naturally occurring radioactive materials in soil, water, and food crops from selected gold mining area in Uganda.

1.3.2 Specific objectives

- (i) To measure the in-situ gamma dose rates in the soil from the selected gold mining area.
- (ii) To determine the levels of naturally occurring materials (^{238}U , ^{232}Th and ^{40}K) in soil, water and foodstuff samples from selected gold mining areas.
- (iii) To estimate the potential environmental and human health risks associated with the consumption of water and foodstuff from selected gold mining area.

1.4 Significance of the study

The study evaluated potential radionuclide contamination resulting from mining activities that pose environmental health and safety risks. The findings contribute to the development of informed policy and regulatory frameworks, thereby promoting environmental sustainability and supporting the economic growth of Uganda's gold mining industry.

The study aligned with Objective 1 of Uganda's Fourth National Development Plan (NDP IV), which emphasizes the sustainable use and management of natural resources, alongside the strengthening of regulatory mechanisms and enforcement against environmental pollution and degradation.

In addition, the study supports the achievement of Sustainable Development Goal (SDG) 3, (Good Health and Well-being), particularly Target 3.9, which seeks to substantially reduce the number of deaths and illnesses caused by hazardous chemicals and pollution of air, water, and soil.

1.5 Justification of the study

Artisanal and small-scale gold mining and processing activities in Uganda generate substantial amounts of waste, which are suspected to contain Naturally Occurring Radioactive Materials (NORMs). Elevated levels of these radionuclides in the environment can lead to the contamination of soil, water, and the food chain, ultimately posing serious health risks to humans including genetic damage, increased cancer risk as well as ecological toxicity affecting both fauna and flora. Despite these concerns, no comprehensive research has been conducted in Uganda to quantify the levels of radioactivity resulting from NORMs in gold mining areas or to estimate the potential health risks associated with the consumption of contaminated water and food from such regions.

The study determined radionuclide levels in gold mining areas of Uganda which provided critical insights into the environmental impact of mining on natural resources such as soil, water, and food crops. Furthermore, it aligned with sustainable resource management goals by identifying contamination levels, informing mitigation strategies, guiding food safety policies, and helping to reduce potential health risks from exposure to contaminated food and water supplies.

1.6 Conceptual framework

This structure helped to visualize how different factors contribute to the levels of radionuclides contamination in various environmental matrices, and allows the study to conclude the effects of mining practices on public health and the environment as shown in Fig 1.1.

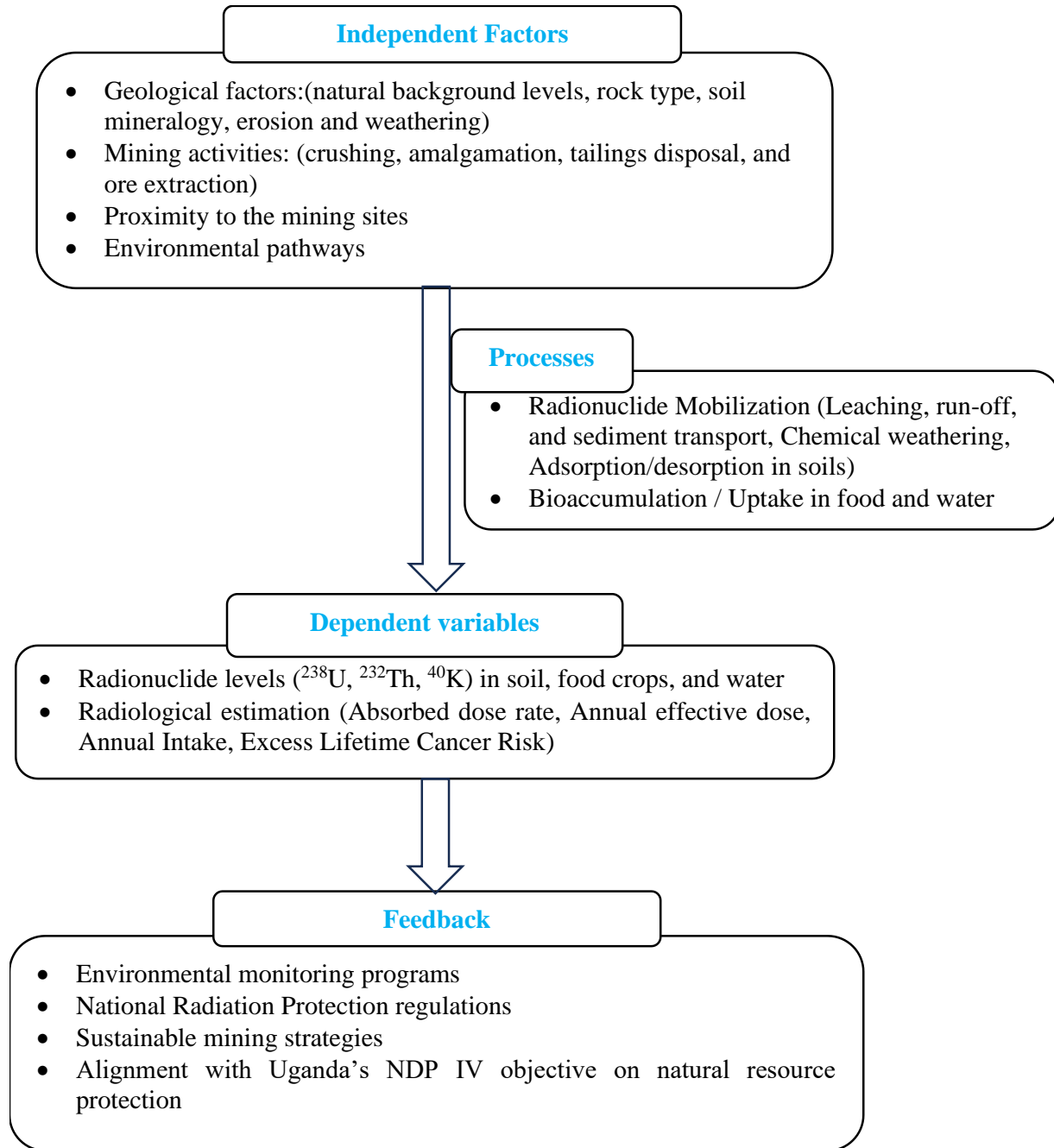


Figure 1. 1: Conceptual framework

1.7 Scope

This study focused on selected gold mining areas in Uganda, specifically Kassanda, Buhweju, and Namayingo, that predominantly practice Artisanal and Small-scale gold mining (ASGM). The sites were deliberately selected to capture a broad and representative range of mining environments, geological features, degrees of environmental disturbance, distances from ore-processing areas, and differences in operational techniques. This diversity was anticipated to enhance the generalizability of the study's findings across different mining contexts in the country. To ensure comprehensive and reliable data, the study involved the collection and analysis of ambient matrix samples, including soil, sediments, water, and locally grown foodstuffs (cassava tubers and tea leaves). This integrative approach allowed a broader, more accurate, and interpretable assessment of environmental radioactivity, increasing the confidence in the validity and effectiveness of the research outcomes. Sampling during the dry season was preferred to minimize dilution effects, reduce hydrological redistribution of radionuclides, and obtain stable and representative activity concentrations in soils, water, and foodstuffs from gold mining environments.

The analysis focused on the determination of NORMs using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) as the analytical technique for precise and sensitive measurement of radionuclide concentrations in the collected samples.

CHAPTER TWO: LITERATURE REVIEW

2.1 Artisanal gold mining in Uganda

Artisanal and small-scale gold mining involves the manual extraction of gold from open pits using hand tools, followed by drying and crushing (Wanyama et al., 2020). Uganda's gold mining industry is mostly focused in a few areas, such as Buhweju, Namayingo, Karamoja, Mubende and Kassanda Districts (Kaggwa et al., 2024). According to Verbrugge & Geenen (2020) and Njieassam (2023), the majority of mining operations in these regions are artisanal and small-scale gold mining (ASGM), which is distinguished by unregulated operations, a high degree of manual labor, and informal procedures. Although Uganda has a wealth of mineral resources, artisanal miners dominate the country's mining industry, even though large-scale production of development and valuable minerals is also possible. The activities associated with mining, including excavation, crushing, milling, and waste disposal, can mobilize radionuclides into the surrounding soil, air, and water, thereby increasing potential exposure risks.

Consequently, long-term exposure to low doses of radiation, particularly among small-scale miners and communities living near mining areas, is of major concern. This exposure is exacerbated by inadequate ventilation in mines, insufficient protective equipment, and limited public awareness about radiation risks (Asere & Ajayi, 2015). Mining has therefore been identified as one of the possible exposure source to naturally occurring radioactive materials especially when radioactive waste is inadequately managed (Faanu et al., 2011). Gold mining has been identified as a significant source of NORMs in the environment, due to the disturbance of geological formations during mineral extraction processes (Nabayaogo et al., 2022). Since some miners spend the majority of their time in underground mining tunnels, particularly in artisanal and small scale gold mining, there is also a chance that they could be exposed to radiation dosages during the excavation, extraction, transportation, and processing of gold (Wanyama et al., 2020). Proximity to gold mines often correlates with elevated radiation levels in the environment, which may accumulate over time and contribute to health conditions such as skin cancer, lung cancer, bone cancer, and leukemia (UNSCEAR, 2000; Odelami et al., 2024).

2.2 Gold mineralisation in gold mining areas in Uganda

Gold mineralization refers to the natural geological process by which gold concentrates in the Earth's crust, forming economically valuable deposits. This occurs through several processes, including hydrothermal activity where mineral-rich fluids circulate through rock fractures and precipitate gold, often associated with quartz veins and sulfide minerals. Gold mineralization is commonly controlled by structural features such as faults and shear zones, which act as pathways for these fluids (Nyakecho & Hagemann, 2014). It can also result from weathering and mechanical concentration processes that form placer deposits. A significant type of gold mineralization is orogenic gold deposits, which form in metamorphic belts during tectonic events, where gold-bearing fluids migrate through structural discontinuities and precipitate at mid-crustal depths, creating veins rich in gold and associated elements (Gabert, 1990).

The gold deposits in Uganda were discovered as early as 1933, with significant reserves in areas such as Kahengyere and Muti within Buhweju. Besides gold, Buhweju District also has proven reserves of copper, lime, and timber, contributing to its economic potential (Bahiru & Woldai, 2016). While gold mining in Buhweju provides vital income and employment opportunities that support local livelihoods, it also presents significant challenges related to poor working conditions, environmental degradation, health risks, and limited community empowerment, especially for women miners. Addressing these issues is crucial for sustainable economic benefits to the local community.

The majority of gold mineralization in Uganda are hosted by a range of host rocks and metamorphic grades, which were created as a result of orogenic activity from the Archean (such as the Busia gold district in the Busia-Kakamega greenstone belt) to the Paleoproterozoic (e.g. Mubende and Buhweju-Mashonga gold districts in the Rwenzori fold belt), the Mesoproterozoic (such as the Kabale-Kisoro area in the North Kibaran fold belt) and the Neoproterozoic (e.g. the Karamoja gold district in the Mozambique fold belt and Kitgum area are important gold-bearing regions (Nyakecho & Hagemann, 2014).

Geologically, Gold is mined on small-scale artisanal levels and through industrial operations in Uganda. Deposits are found in quartz veins and underground formations (Bahiru & Woldai, 2016). Despite historical occurrences and recognized artisanal mining, there is currently little modern exploration in Uganda, and research into the specific controls on gold mineralization is ongoing to

better understand the origins and distribution of these deposits, according to miners. This geological setting highlights Uganda's considerable potential for gold mineralization in its Archean and Proterozoic terranes, which are governed by tectonic development, metamorphism, and lithology.

Artisanal and small-scale Mining (ASM) has become widespread across Uganda and has been growing at an exponential rate since 2008. ASM constitutes over 90% of the minerals produced in Uganda (Sebina-Zziwa & Kibombo, 2020). This suggests that many mining operations, including gold mines, are not adequately observed and assessed, which could have a significant impact on the environment, particularly wetlands. In Uganda's tropical watersheds, artisanal gold mining activities continue to degrade aquatic resources (Barasa et al., 2016), impacting the wetland vegetation that is a component of the watershed areas (Castendyk & Webster-Brown, 2007; Mpamba et al., 2008). However, because of the abandonment of mined pits, the extent of degradation brought on by gold mining distorts and damages the earth's surface, ruining the landscape scenery (Barasa et al., 2016). One of the wetlands in the Buhweju district is Bitsya Sub-county, where small-scale artisanal gold mining is carried out.

2.2.1 Overview of radionuclide formation in the environment

Radionuclides are formed through both natural and anthropogenic processes that alter the stability of atomic nuclei. Naturally occurring radionuclides originate from three main sources: primordial radionuclides, such as ^{238}U , ^{232}Th , and ^{40}K , which were created during the formation of the Earth and persist due to their incredibly long half-lives; cosmogenic radionuclides, which are continually generated in the atmosphere when cosmic rays interact with elements like nitrogen and oxygen; and radiogenic radionuclides, which arise as decay products within the uranium and thorium series. In addition to these natural sources, artificial radionuclides are generated through human activities including nuclear reactor operations, particle accelerator reactions, and previous nuclear weapons testing (Focus et al., 2021b). The distribution and behavior of radionuclides in different environmental matrices are influenced by these activities, which release more unstable isotopes into the environment.

2.2.2 Partial distribution of radionuclides commonly associated with gold mining

The spatial distribution of radionuclides frequently associated with gold mining operations is shown in this section, highlighting how they vary across environmental media and sampling sites.

Table 2. 1: Spatial distribution of radionuclides in gold mining areas

Radionuclide	Decay series / origin	Typical host minerals in gold ores	Environmental medium	Relevance in gold mining areas
Uranium-238 (²³⁸ U)	Uranium decay series	Uraninite, pitchblende, zircon, monazite	Soil, tailings, rock, water	Occurs in hydrothermal gold deposits and granitic host rocks; major source of radiological contamination
Thorium-232 (²³² Th)	Thorium decay series	Monazite, thorite, allanite	Soil, sediments, tailings	Associated with heavy minerals in gold-bearing formations; contributes to the external gamma dose
Radium-226 (²²⁶ Ra)	Decay product of ²³⁸ U	Secondary minerals in mine wastes	Water, soil, tailings	Mobile in groundwater; contributes to the ingestion dose
Radon-222 (²²² Rn)	Gaseous decay product of ²²⁶ Ra	Released from fractured ore and tailings	Air	Causes internal exposure through inhalation in mine environments
Lead-210 (²¹⁰ Pb)	Decay product of ²²² Rn	Adsorbed on fine particles	Soil, vegetation	Indicator of atmospheric redistribution from mine sites
Polonium-210 (²¹⁰ Po)	Decay product of ²¹⁰ Pb	Sulphide minerals	Food crops, water	Important for ingestion dose assessment
Potassium-40 (⁴⁰ K)	Naturally occurring radionuclide	Feldspar, mica, clay minerals	Soil, rock, water, crops	Present in host rocks; contributes to background radiation
Thorium-228 (²²⁸ Th)	Decay product of ²³² Th	Monazite-bearing sands	Soil, sediments	Enhances gamma radiation levels in mining zones
Uranium-235 (²³⁵ U)	Naturally occurring uranium isotope	Uraninite, coffinite	Rock, tailings	Minor contributor but relevant for nuclear energy potential

2.3 Environmental pathways and distribution of radionuclides in gold mining areas

The distribution of radionuclides in gold mining areas is influenced by geological, hydrological, and mining-related factors (Olagbaju et al., 2021). In gold mining regions, radionuclides are dispersed through the lithosphere (rocks and soil), hydrosphere (water), atmosphere (air and dust), and biosphere (plants, animals, and humans). The lithosphere is the primary source of

radionuclides such as ^{238}U , ^{232}Th , and ^{40}K , which are abundant in granitic and volcanic rocks (Ugbede & Echeweozo, 2017). Gold mining exposes and concentrates these elements in mine tailings and waste rocks, increasing soil contamination. Both natural and anthropogenic activities contribute to soil radioactivity (Akpanowo et al., 2020). Radionuclides in soil can enter plants and water systems, affecting ecosystems and human health through ingestion, inhalation, or absorption (Sheppard, 2011). Factors such as geology, mining intensity, and soil type influence radionuclide concentration (Focus et al., 2021b). The hydrosphere is fundamental to the existence of life and ecological balance, as it is essential to both biotic and abiotic elements of the ecosystem. Within living organisms, water plays a several essential roles, including solvent, buffer, metabolite, and lubricant (Kotwicki, 1991). Thus, it is clear that access to water and its quality are critical to health. Radionuclides are leached from rocks and tailings into surface and groundwater, often accelerated by acid mine drainage (Kasimbazi, 2019). Uranium, being soluble in oxidizing conditions, easily contaminates water, while thorium and radium migrate through colloids. Contaminated water affects drinking supplies and aquatic life, spreading radioactivity beyond mining sites (Barasa et al., 2016). Geological composition, mining practices, and seasonal variations influence radionuclide levels. Studies show that mining often results in acidic, turbid, and particle-rich waters containing uranium, thorium, radium, and heavy metals (Winde et al., (2019); Focus et al., (2021a); Ayiwouo et al., (2022).

In the atmosphere, mining and ore processing release radioactive dust and radon gas (^{222}Rn) posing inhalation risks to workers and nearby residents, potentially increasing cancer risks due to prolonged exposure (Kasimbazi, 2019). Within the biosphere, radionuclides enter the food chain through plant uptake, water contamination, and atmospheric deposition. Aquatic organisms and crops can accumulate uranium, thorium, and radium, which are then transferred to humans via food and water consumption or inhalation (El-Arabi, 2007; Shanthy et al., 2012). Ingestion of radionuclides contributes significantly to internal radiation doses, accounting for 30–60% of total internal exposure from natural sources (UNSCEAR, 2000). Continuous exposure through contaminated food and water poses potential long-term health risks including cancer and organ damage (Amin & Ahmed, 2013).

2.4 Transfer of radionuclides from soil to humans

The transfer factor (TF), which is the ratio of radioactive concentration in plant to soil per unit mass, is used to assess the uptake of radionuclides from soil to plants (Napier et al., 2003). This parameter is required for environmental transfer models, which help estimate the dosage impact on humans by predicting the concentration of radionuclides in crops (Kolapo, 2019; T. C et al., 2023). In a study, the activities of NORMs were effectively assessed using gamma-ray spectrometry on rice plants as well as on corresponding soil samples that were taken from paddy fields in Penang, Malaysia and according to the results, the distributions of the chosen radionuclides in rice vary depending on the type of component or material (Alsaffar et al., 2015).

Radionuclide uptake by plant roots is a competition-based process associated with plant physiology (UNSCEAR, 2008b), and can be reintroduced into the atmosphere through wind and raindrops, increasing food contamination (Naletoski et al., 2021; Sheppard, 2011). Human exposure is linked to soil radionuclide content, nutrient absorption, soil properties, and food consumption rates (Hassan et al., 2021a). One of the main routes by which radionuclides can enter the human body is through the soil, plants, and people. Through plant roots systems, radionuclides including ^{40}K , ^{238}U , ^{226}Ra , and ^{232}Th , as well as their decay daughters, can enter the food chain after being deposited in the soil (Zango et al., 2013).

The composition of soil determines how NORMs are transferred from soil to plant, how they are distributed across various plant compartments, and how much of each element is consumed by humans when plant crops are consumed. The metal-selective function of plants during element uptake in order to maintain the mechanism of homeostasis in normal conditions affects the degree of accumulation of natural radioactive elements (Shanthi et al., 2012). By way of ingestion, these substances may accumulate in specific body organs, resulting in radiotoxicity and disruption of regular processes (Oladele et al., 2022).

The transfer factor (TF) is important for evaluating environmental radioactive pollution and human health hazards. Several literature including Alharbi & El-Taher, (2013), Gaffar et al., (2014), Adesiji & Ademola, (2019), (Kolapo, 2019), Elsaman et al., (2020), A. Gregory et al., (2020), Elsaman et al., (2020), Rout et al., (2021), explain soil to crop transfer factor (TF) as a key parameter used to assess radioactive contamination in the environment, internal radiation dose for the ingestion pathway, and its risks to humans.

2.5 Radionuclides in gold mining areas

According to some studies, Akpanowo et al., (2020), Focus et al., (2021a), Ayiwouo et al., (2022) the environment may become more abundant in radionuclides, including uranium (U), thorium (Th), and radium (Ra) as a result of gold mining operations. Mining, milling, and the disposal of tailings are some of the ways that these radionuclides might be emitted. Tailings are the fine-grained waste materials left after the extraction of gold from ore, consisting of crushed rock and leftover minerals. Human health can be seriously endangered by radionuclide exposure, which can raise the risk of cancer and other illnesses (Peter et al., 2022). It has been observed that gold deposits and other metal ores in Africa have large amounts of naturally occurring radionuclides and during mining operations and ore processing, these radionuclides may be discharged, potentially rendering the mining waste rocks useless and exposing local residents and mine workers to dangerous radiation levels (Nabayaogo et al., 2022).

Gold ores can contain natural radioactive elements such as uranium and thorium. Mining and processing these ores can release these elements into the environment (Moshupya et al., 2022). Studies have demonstrated the environmental impact of gold mining on soil and water, revealing elevated levels of radiation and associated health risks (Mohamed et al., 2024). Because naturally occurring radionuclides can enter the food chain through plant roots and enter the edible parts of plant tissues from the contaminated topsoil, they pose a radiation health risk to humans (Muhoozi et al., 2023).

In such cases, gold mining wastes contain high concentrations of uranium and uranium daughters and the implementation of protective measures is often needed (Faanu et al., 2011). According to a recent assessment, the local population's exposure to uranium from these tailings is radiologically concerning (Focus et al., 2021a). Several authors (El-Gamal et al., 2019; Wanyama et al., 2020) have reported higher levels of radioactivity in the gold mine tailings and soil in the province of Gauteng in South Africa, and food stuffs from Delta Abyan, Yemen, as well as higher concentrations of ^{226}Ra , ^{232}Th , and ^{40}K than the global average in gold mine soil samples from South Africa, Brazil, and Rwanda (Nabayaogo et al., 2022).

Previous assessments by several researchers including (Silver et al., 2016; Yachiso & Chaubey, 2020; Amos et al., 2022) in Uganda indicated varying levels of natural radionuclides in soils from different regions, which could translate to variability in crop contamination levels posing a health

risk to the inhabitants. Uganda's geology, rich in minerals like uranium, suggests a potential for elevated natural radioactivity in mining areas (Turyahabwe et al., 2024).

2.5.1 Applications of radionuclides associated with gold

In nuclear medicine imaging, radionuclides are widely used as radiotracers to visualize organ structure and function. After administration in very small, safe quantities, they emit gamma rays or positrons that are detected by imaging systems (Andersson et al., 2017). Radionuclides are also used to destroy diseased tissues, particularly cancer cells, by delivering targeted radiation doses. e.g., Iodine-131 (^{131}I) treatment of hyperthyroidism and thyroid cancer, Cobalt-60 (^{60}Co) external beam radiotherapy. Selectively damages diseased cells while minimizing harm to healthy tissues and can be combined with surgery or chemotherapy (UNSCEAR, 2000).

Gamma-emitting radionuclides are also used to sterilize medical supplies such as syringes, surgical gloves, catheters, and bandages. Cobalt-60 kills bacteria and viruses without using heat or chemicals, and is suitable for heat-sensitive equipment (UNSCEAR, 2000).

Radionuclides are used as tracers to study metabolic pathways, drug distribution in the body, blood circulation, and organ uptake. In agriculture, they are utilized as tracers for studying nutrient uptake, fertilizer efficiency, and water movement. Isotopes like phosphorus-32 and nitrogen-15 enhance fertilizer utilization by examining metabolic pathways. They also play a role in food preservation by eliminating pathogens and extending shelf life. Furthermore, radiation is employed in mutation breeding to create crop varieties resistant to pests and environmental challenges, alongside the sterile insect technique for pest control (IAEA, 2004).

Radionuclide techniques support public health and disease management, especially early cancer screening, assessment of organ function, monitoring of treatment response and control of thyroid disorders (Uddin et al., 2022).

In industrial non-destructive testing (NDT), radionuclides are often utilized to find structural flaws in materials like pipes and welds without causing damage. Cobalt-60 and iridium-192 are two common gamma-emitting radionuclides used in industrial radiography. They also function as thickness, density, and level gauges to ensure quality control in the production of metals, paper, and plastics. In complex industrial systems, tracer techniques also make leak detection and fluid flow monitoring easier (IAEA, 2004).

Radionuclides are essential for environmental monitoring and hydrology, helping to trace pollutant transport in surface and groundwater. Naturally occurring and anthropogenic radionuclides like lead-210 and cesium-137 are utilized to analyze sedimentation rates, soil erosion, and depositional histories, offering insights into the environmental impacts of mining, industry, and land-use changes (UNSCEAR, 2008a). In geology, uranium–lead, potassium–argon, and rubidium–strontium dating methods are crucial for figuring out how old rocks and minerals are, helping to reconstruct geological time scales and tectonic histories, and improving our comprehension of Earth's evolution and human history.

Radionuclide techniques are used in forensic science and security to discover illicit items in border security, cargo screening, and explosive detection. In order to enhance regulatory enforcement and non-proliferation initiatives, nuclear forensic techniques use radionuclide signatures to ascertain the origin and history of radioactive materials.

2.6 Health effects of radionuclides

2.6.1 Cancer

The primary long-term health concern for consumers due to high radiation exposure is the development of cancer. Radionuclides influence the target organs and the types of cancer that may develop (Amin & Ahmed, 2013). Lung and thyroid cancers, DNA damage and leukemia are more likely to occur after a prolonged period of exposure to lower ionizing radiation levels. (Francisca et al., 2023). Previous studies have documented the impact of gold mining activities including risks of cancer associated with water and foodstuff ingestion calculated through the estimation of the Excess Lifetime Cancer Risk (ELCR) (Mohuba et al., 2022).

2.6.2 Immune system suppression

Significant buildups of radioactive species in particular organs result in morphological or biochemical alterations. As a result, the body's defenses against certain diseases may be weakened. One of the contributing causes of radiation carcinogenesis and, thus, higher death rates would be the immune system's impact (Amin & Ahmed, 2013). Gamma radiation from NORMs is extremely penetrating and poses a risk of external radiation exposure that can result in whole-body exposure and systemic health impacts (Talapko et al., 2024). Hence, immune systems deteriorate, different diseases and tumors arise, and the death rate rises (Amin & Ahmed, 2013).

2.6.3 Genetic mutations and reproductive effects

Radiation exposure may alter the genetic code of cells, resulting in genetic mutations in reproductive cells that can cause birth defects and hereditary effects (Chaturvedi & Jain, 2019). Radiation strikes the DNA molecule directly in the direct action, causing the molecular structure to be disrupted (Asere & Ajayi, 2015). The primary cause of radiation's long-term damage to the body's organs and tissues is damage to DNA in the nucleus (IAEA, 2023). Even at the lowest doses, single radiation tracks can result in double-strand breaks and, if not repaired completely, might cause long-term harm (UNSCEAR, 2000).

2.7 Assessment of Radiological Hazards

Health risk assessment quantitatively evaluates the potential of pollutants to harm human health and provides a scientific basis for determining pollution control and environmental governance priorities (M. Yang et al., 2023). The radiological health risk parameters include the average values of radium equivalent activity (Raeq), absorbed dose rate (D), annual effective dose rate (AEDE), hazard indices and excess life cancer risk (ELCR) according to C. P. Ononugbo et al., (2019), Wanyama et al., (2020), Joel et al., (2021), Kadiri et al., (2022), Hasson et al., (2022), Shi et al., (2024).

2.7.1 Absorbed dose, D

The amount of energy deposited by ionizing radiation per unit mass of tissue, measured in grays (Gy). (Avwiri, Ononugbo, & Nwokeoji, 2014). Absorbed dose is directly related to deterministic effects (tissue reactions) such as acute radiation syndrome, which occur above certain dose thresholds. For example, whole-body absorbed doses of 1–2 Gy may cause nausea and vomiting, while doses above 6 Gy can be fatal without medical intervention.

2.7.2 The effective dose, ED

This provides a measure of overall health risk from exposure. ICRP considers the control of public exposures in planned, existing and emergency situations using effective dose, calculated using tissue weighting factors that relate to overall detriment (Puncher et al., 2017). It is the most commonly used quantity to estimate the stochastic effects (cancer and hereditary effects) in medical radiology is (Andersson et al., 2017). When the total dose in the body exceeds 2 Gy, the impact of stochastic effects to the overall chance of an early, premature death is minimal (IAEA, 2023). The recommended dose is assessed for children and infants up to the age of 70 years

(UNSCEAR, 2000). Several studies including Moshupya et al., (2022), Ademola et al., (2014), Focus et al., (2021b) have shown the mean annual effective dose in the gold mining sites higher than the world average in soils.

2.7.3 Excess Lifetime cancer risk, ELCR

This is the radioactive factor used to assess whether exposure to gamma radiation has resulted in lethal cancer over a given period of exposure (Kolo et al., (2020), Fasanmi et al., (2021), Adel et al., (2022). It shows how many more incidences of cancer are anticipated in a specific group after exposure to ionizing radiation (Habakwiha et al., 2023), and genetic effects. Studies have reported ELCR values ranging from about 0.29×10^{-3} (standard average) to values exceeding 1×10^{-3} in areas with enhanced radionuclide concentrations, such as quarry sites where excavation increases radionuclide exposure Ugbede & Echeweozo, (2017) and Akpanowo et al., (2020). Values above the typical reference level suggest a higher probability of lifetime cancer risk, indicating a need for radiation protection measures.

Table 2. 2: Documented formula and safe limits for health assessment estimation

Parameter	Formula/Definition	Safe Limit	Reference
Raeq	$A_U + 1.43A_{Th} + 0.077A_K$	$\leq 370 \text{ Bqkg}^{-1}$	(Durusoy & Yildirim, 2017)
D	$0.462A_U + 0.604A_{Th} + 0.0417A_K$	59 nGyh^{-1}	(UNSCEAR, 2000)
Hex / Hin	Derived from activity	≤ 1	(UNSCEAR, 2000)
AEDE	Dose \times Time \times Factors	$\leq 1 \text{ mSvyr}^{-1}$	(ICRP, 2007)
ELCR	AEDE \times DL \times RF	$\leq 0.29 \times 10^{-3}$	(UNSCEAR, 2000)

2.7.4 Annual intake (I)

Annual Intake (I) is the amount of a specified radionuclide entering the human body by ingestion or inhalation within one year. It is a term used in radiological and health risk assessments to quantify the total exposure through a specific pathway and is an essential parameter for calculating annual effective dose or health risk, such as cancer risk from radionuclides (ICRP, 2007). The committed effective dose is obtained by multiplying the activity intake by the effective dose coefficient for the indicated route of intake, typically inhalation or ingestion (Authority et al., 2018; Alonso et al., 2006).

Humans are mostly exposed to natural radionuclides through food (cereals, vegetables, tubers, fruits, meat, fish, milk, etc.) and drinking water. Estimating annual intake (Bqy^{-1}) and the related annual effective dose (Svy^{-1}) is a key task in radiological environmental assessment because it links measurable activity concentrations in environmental media to potential impacts on human health. Important components of such research investigations include measured radioactivity levels in specific foods and water, actual consumption rates for the population of concern, and ingestion dose coefficients that convert ingested activity to effective dosage (ICRP, 2007).

Various studies including Asaduzzaman et al., (2015), Hassan et al., (2021b) and (Osanai et al., 2021) have estimated the annual intake of NORMs in different foodstuffs and water and used it to calculate annual effective dose due to ingestion. Ingesting radionuclides through food may be one of the main causes of chronic illnesses, since it may contribute greatly to the average radiation doses to various body organs (Jibiri et al., 2007a).

2.8 Regional studies in East Africa

A study in Northern Uganda found that the concentrations of primordial radionuclides, including ^{238}U , ^{232}Th , and ^{40}K , were above the world limit, indicating the presence of radioactive minerals (Amos et al., 2022). The average activity concentrations of ^{238}U , ^{232}Th and ^{40}K in sediments from Gulu and Amuru districts in Uganda were higher than the global limits. Hence, the study area is rich in uranium and thorium bearing minerals (Gulu et al., 2023). The specific activities for ^{238}U , ^{232}Th , and ^{40}K obtained in a study to determine radioactivity levels and dose rates due to natural radionuclides in rocks from various mines and quarries in Eastern Uganda ranged from 13.95 ± 0.31 to $698.02 \pm 3.38 \text{ Bqkg}^{-1}$ for ^{238}U , 98.68 ± 1.30 to $2397.78 \pm 19.64 \text{ Bqkg}^{-1}$ for ^{232}Th , and 45.97 ± 2.48 to $2183.80 \pm 17.89 \text{ Bqkg}^{-1}$ for ^{40}K . Additionally, the annual outdoor effective dose rates ranged from 0.30 to 1.37 mSvy^{-1} , exceeding the global average of 0.07 mSvy^{-1} by a significant margin (Charles, 2001). This demonstrates how mining operations have raised background radiation levels, raising the possibility of radioactive risks to local residents and workers (Silver et al., 2016).

There are environmental impacts from gold mining in Uganda that relate to siltation of rivers and wildcat pitting causing localized degradation of soil and vegetation (in some cases affecting forest resources). Particularly in the tropical climate characteristic of the West and Southwest, natural reclamation of sites appears to be relatively rapid. However, in some areas like Buhweju, it has

been noted that having hundreds of miners working in a single watershed can affect downstream water users cumulatively through siltation, create health and safety risks (such as for humans and cattle from wildcat pitting), and hinder post-mining agricultural use (United Nations Environment Programme, 2012).

Some literature including Amos et al., (2022), Peter et al., (2022), Turyahabwa et al., (2024) on the assessment of radioactivity levels and dose rates, radiological hazards due to radionuclides in soils, sediments, and mine tailings from selected mining areas and quarries in Uganda and they all suggest potential radiological risks linked to natural radioactivity contamination from sediments and mine tailings, especially when used as building materials.

In western Kenya, thirty tailing samples from Rosterman gold mine site were analysed to determine the radiological risks associated with naturally occurring radionuclides in materials from the Rosterman gold mine. The average activity concentration for ^{40}K , ^{232}Th , and ^{226}Ra was 263 ± 13 , 123 ± 6 , and $84 \pm 4 \text{Bqkg}^{-1}$, according to the gamma-ray spectrometric measurement of tailing samples. The annual effective dose was reported to be $0.4 \pm 0.02 \text{mSvy}^{-1}$ indoors and $0.3 \pm 0.01 \text{mSvy}^{-1}$ outdoors, with an average absorbed dose rate of $124 \pm 6 \text{nGyh}^{-1}$. Therefore, the tailing samples recorded absorbed doses and radiological indices were below the world average permissible values. This implies that the radiation exposure to the miners and general public due to tailing wastes at Rosterman gold mine poses no significant health risk (Wanyama et al., 2020).

The radioactivity linked to ASGM operations along the Ulindi River in the eastern Democratic Republic of the Congo was assessed using inductively coupled plasma–mass spectrometry and gamma-ray spectrometry on soil and sediment samples. The activity concentrations of ^{238}U (up to $3127 \pm 98 \text{Bqkg}^{-1}$), ^{226}Ra (up to $2710 \pm 89 \text{Bqkg}^{-1}$), and ^{232}Th (up to $2142 \pm 162 \text{Bqkg}^{-1}$) were found to be 71–89 times higher compared to the global average concentrations reported by UNSCEAR in soils. Due to the large amounts of primordial radionuclides found in gold deposits in that area, the average ambient effective radiation dose rate was found to be 8.4mSvy^{-1} (range 0.5 to 40mSvy^{-1}). This region can fall under the category of a natural high background radiation area (HBRA). Radiological criteria were used to evaluate the radiation risk to the people and artisanal miners who worked with certain geological elements. such as excess lifetime cancer risk, outdoor gamma absorbed dose rate, annual effective dose equivalent, and radium equivalent activity index. The average values of these measurements were far higher than the global standard

and suggested that there were substantial radiation hazards for both local residents and gold miners. To safeguard local residents and employees in this area, a radiation safety strategy appears to be necessary (Atibu et al., 2022).

2.9 Global perspectives on gold mining and radioactivity

The United Nations Scientific Committee on the Effects of Atomic Radiation has recognized artisanal gold mining as one of the anthropogenic activities that may expose people to naturally occurring radionuclides. In one study, for instance, Kolo et al. (2020) used a gamma spectrometric technique that uses a NaI (Tl) gamma-ray detector to evaluate the natural radioactivity of 40 surface soil samples that were randomly selected from the Gababiyu artisanal gold mining location in Minna Metropolis, Nigeria. The specific activities of ^{226}Ra , ^{232}Th and ^{40}K in the soil varied from $10.272.88 \pm \text{Bqkg}^{-1}$ to $152.60 \pm 3.80 \text{ Bqkg}^{-1}$, $32.67 \pm 1.93 \text{ Bqkg}^{-1}$ to $185.90 \pm 6.06 \text{ Bqkg}^{-1}$ and $35.18 \pm 1.45 \text{ Bqkg}^{-1}$ to $947.50 \pm 7.51 \text{ Bqkg}^{-1}$ respectively, with mean values of $65.06 \pm 4.20 \text{ Bqkg}^{-1}$, $87.63 \pm 2.89 \text{ Bqkg}^{-1}$ and $267.94 \pm 4.29 \text{ Bqkg}^{-1}$ in sequence. Even though ^{226}Ra and ^{232}Th recorded activity values that are marginally higher than the global average, they remain within the UNSCEAR-recommended safety range. At one meter above the ground, the calculated average absorbed dose rate was 94.16 nGyh^{-1} , and the corresponding mean annual dose equivalent was 0.12 mSvy^{-1} . Additionally, the computed average excess lifetime cancer risk was 0.40×10^{-3} , which is somewhat higher than the UNSCEAR safety threshold (Kolo et al., 2020).

In Central Nasarawa State, Nigeria, a study was carried out to ascertain the concentrations of ^{226}Ra , ^{232}Th , and ^{40}K natural activity in the surface soils and sediments of certain mining regions. For ^{40}K , ^{226}Ra , and ^{232}Th , the mean natural activity concentrations measured from the examined samples were $403.963 \pm 7.29 \text{ Bqkg}^{-1}$, $32.52 \pm 4.65 \text{ Bqkg}^{-1}$, and $56.23 \pm 2.30 \text{ Bqkg}^{-1}$, respectively. With the exception of ^{232}Th , which differs by 20.23 Bqkg^{-1} from the world average value, the results were somewhat below the world average value. The calculated mean effective dosage per year was $0.04 \pm 2.7 \text{ mSvy}^{-1}$. The yearly dosage limit for the general public is far higher than this. At the two locations, the average background radiation absorbed doses are $5.81 \pm 0.08 \text{ mSvy}^{-1}$ and $8.45 \pm 0.56 \text{ mSvy}^{-1}$ (Ibrahim, U., Akpa, T. C., & Daniel, 2013). This is greater than the global average of 1 mSvy^{-1} reported by UNSCEAR, (2000).

Using the gamma spectrometry technique, this study evaluated the activity concentrations of ^{238}U (^{226}Ra), ^{232}Th , and ^{40}K and the radiological risks associated with soil exposure and food crop

consumption in Babban Tsauni artisanal gold mine, Gwagwalada, Nigeria. The mean activity concentrations (levels) of ^{226}Ra , ^{232}Th , and ^{40}K in the mine soil were 46.4 ± 49 , 79.9 ± 39.3 , 266.4 ± 185.4 for root tuber and 46.9 ± 15.7 , 100.5 ± 35.8 , 311.4 ± 137.2 (Bqkg^{-1}) for grains. The results show that the activity concentrations of radionuclides in all samples exceeded the recommended values set by the United Nations Scientific Committee on the Effects of Atomic Radiation (33, 45, and 420 Bqkg^{-1}), with the exception of ^{40}K , which was within the acceptable limit in all food crop sample types. The annual effective dose from external gamma radiation in soil and the annual gonadal equivalent dose were significantly high in all samples examined; these necessitate ongoing radiological monitoring. Estimated results for radiological hazard parameters, radium equivalent, annual effective dose from ingestion, and excess life cancer risk were within safe limits (Odelami et al., 2024).

An evaluation of the radiological risks posed by gold mine tailings in South Africa's Gauteng Province revealed average specific activity for ^{40}K , ^{232}Th , and ^{238}U . These were $17.0.1 \pm 0.4 \text{ Bqkg}^{-1}$, $22.2 \pm 0.5 \text{ Bqkg}^{-1}$, and $496.8 \pm 15.2 \text{ Bqkg}^{-1}$ for ^{238}U , ^{232}Th , and ^{40}K , respectively, and $785.3 \pm 13.7 \text{ Bqkg}^{-1}$ for ^{238}U , $43.9 \pm 1.0 \text{ Bqkg}^{-1}$ for ^{232}Th , and $427.0 \pm 13.1 \text{ Bqkg}^{-1}$ for ^{40}K in the control area. Both the internal and exterior hazard indices were much greater than the suggested maximum allowable limit of unity, at 2.4 and 4.5, respectively. This indicates that the public and employees are at serious risk for health problems due to the high amounts of gamma radiation in this area (Kamunda et al., 2016).

In a study, using gamma ray spectroscopy, the natural radioactivity levels of ^{226}Ra , ^{232}Th , and ^{40}K were determined in water samples from Assiut, Egypt, which showed the high impact of water infiltration from the pond to the subsurface water in the surrounding areas was explained by the high activity concentrations for ^{226}Ra , ^{232}Th , and ^{40}K found in water samples. Such infiltration facilitates the mobilization and transport of naturally occurring radionuclides from mineralized soils and sediments into groundwater, particularly in areas underlain by uranium- and thorium-bearing geological formations. Elevated levels of ^{226}Ra and ^{232}Th are of particular concern due to their radiotoxicity and long half-lives, while ^{40}K contributes to increased external and internal radiation exposure through water use. Consequently, prolonged use of this water for agricultural irrigation may lead to radionuclide accumulation in soils and crops, posing potential radiological risks to both the environment and human health. Therefore, the authors emphasized the need for

cautionary precautions and continuous radiological monitoring before such water resources are utilized for irrigation purposes (El-gamal & El-mageed, 2014).

Guangdong province is known for having a high level of natural background radiation. Using a High Purity Germanium (HPGe) detector-based gamma spectrometry system, the activity concentrations of the naturally occurring radionuclide materials (NORMs) ^{238}U , ^{232}Th , ^{226}Ra , and ^{40}K were determined in 490 surface soil samples that were gathered from various locations around this province. It was found that the radionuclide levels varied from 12.0 to 264.3 Bqkg⁻¹ for ^{238}U (average 79.3 Bqkg⁻¹), 10.3 to 376.0 Bqkg⁻¹ for ^{232}Th (average 101.0 Bq/kg), 7.6 to 298.3 Bqkg⁻¹ for ^{226}Ra (average 75.1 Bqkg⁻¹), and 8.2 to 1747.1 Bqkg⁻¹ for ^{40}K (average 535.8 Bqkg⁻¹). The mean values of radium equivalent activity (Raeq) and external hazard index (Hex) for the soil samples in the study area were calculated to be 260.8 Bqkg⁻¹ and 0.70 respectively. The gamma absorbed dose rates (D) in air range from 13.6 to 381.5 nGyh⁻¹, with an arithmetic average of 120.0 nGyh⁻¹, while the annual effective dose rates (AEDR) were determined to range from 16.7 to 467.8 μSvy⁻¹, with an arithmetic average of 147.2 μSvy⁻¹ (J. Yang & Sun, 2022).

Several studies conducted in gold mining areas across Africa and Asia have documented elevated levels of these radionuclides in soils, often exceeding background concentrations found in non-mining areas (Oyinkanola et al., 2023). For example, research in Tanzania and Nigeria has shown that soil samples collected from mining pits and processing zones typically exhibit higher radioactivity than those from control sites, suggesting that mining activities contribute to increased environmental radiation (Dike et al., 2020, Focus et al., 2021a). Gold mining activities can potentially elevate radioactivity levels in the Earth's crust by introducing underground mineralised ores containing natural radionuclides to the Earth's surface, hence increasing radiation exposure for workers and nearby populations (Moshupya et al., 2022).

In Fiji, gold mining is one of the main industries that may expose workers to naturally occurring radioactive materials (NORMs), which could be harmful to their health. Using a NaI(Tl) detector, the average activity concentrations of uranium (^{238}U), thorium (^{232}Th), and potassium (^{40}K) in soil samples from the Vatukoula, Fiji, gold mining area were calculated. With ^{232}Th absent from the decommissioned site, the activity concentrations for ^{238}U and ^{40}K ranged from 30.7 Bqkg⁻¹ to 175.73 Bqkg⁻¹. Except for ^{232}Th , which should be higher due to the mineral composition of monazite derivatives, the results for ^{238}U , ^{232}Th , and ^{40}K of the commissioned sites were 19.49

Bqkg⁻¹, 123.06 Bqkg⁻¹, and 86.86 Bqkg⁻¹, respectively (Rabuku & Malik, 2020), which are lower than the global averages as per the United Nations Scientific Committee on the Effects of Atomic Radiation report (UNSCEAR, 2000).

The assessment of naturally occurring radionuclide activity concentrations in foodstuffs and their radiological effects is crucial for evaluating internal radiation hazards like cancer in the population (Habakwiha et al., 2023). A person's internal radioactivity will rise as a result of eating contaminated food, thus increasing their radiation exposure and potentially raising the health dangers of radiation exposure. The type and quantity of radionuclides consumed will determine the precise health impacts (WHO & FAO, 2011).

Using the gamma spectrometry technique, the study revealed the activity concentrations of ²³⁸U (²²⁶Ra), ²³²Th, and ⁴⁰K, as well as the radiological risks associated with soil exposure and food crop consumption in the Babban Tsauni artisanal gold mine, Gwagwalada, Nigeria. The mean activity concentrations of ²²⁶Ra, ²³²Th, and ⁴⁰K in the mine soil were 46.4 ± 49, 79.9 ± 39.3, 266.4 ± 185.4 for root tuber and 46.9 ± 15.7, 100.5 ± 35.8, 311.4 ± 137.2 (Bqkg⁻¹) for grains. The results show that the activity concentrations of radionuclides in all samples exceeded the recommended values set by the United Nations Scientific Committee on the Effects of Atomic Radiation (33, 45, and 420 Bqkg⁻¹), with the exception of ⁴⁰K, which was within the acceptable limit in all food crop sample types. The annual effective dose from external gamma radiation in soil and the annual gonadal equivalent dose were significantly high in all samples examined, necessitating ongoing radiological monitoring. Estimated results for radiological hazard parameters, radium equivalent, annual effective dose from ingestion, and excess life cancer risk were within safe limits (Odelami et al., 2024). While many measurements use gamma spectrometry and ICP-MS for detailed radionuclide analysis, field-based quantification of soil radioactivity is essential for environmental monitoring and risk assessment. The Geiger-Müller (GM) counter provides a rapid and practical method for assessing ionizing radiation levels in situ (Hossen et al., 2022).

Studies for example; (Focus et al., 2021b, Orosun et al., 2022, Odelami et al., 2024) estimated hazard indices were below or within the recommended limits in food, soil and water. According to some studies, like (Dike et al., 2020, Hasson et al., 2022 and Ogungbemi et al., 2023) reveal that the radiological hazards associated with exposure to NORMs from gold mine areas were evaluated due to geology and human activities including gold mining. For-example Akpanowo et

al., (2020) assessed the radiological risks and natural radioactivity levels in environmental samples from artisanal mining sites in Anka, North-West Nigeria and found out that it was attributed to the geology and human activity in the research area are responsible for the higher values. Compared to other parts of Nigeria, this study found a higher excess lifetime cancer risk; long-term exposure for workers and residents of mineral processing communities may raise cancer risks.

2.10 Uganda regulatory framework and international guidelines

International guidelines and organizations including IAEA, WHO, ICRP aim at safeguarding human health and the environment. The IAEA is a key player in establishing radiation protection safety regulations (IAEA, 2016). Additionally, IAEA assists member nations with radioactive emergency monitoring, assessment, and reaction preparation. While occupational exposure is normally regulated at 20 mSv^{-1} averaged over five years, the public exposure limit is usually set at 1 mSv^{-1} above baseline (Wilds, 2013).

According to estimates from the United Nations Scientific Committee on the Effects of Atomic Radiation, the average yearly exposure per person worldwide from all environmental radiation sources is roughly 3.0 mSv^{-1} . Radiation from naturally occurring sources accounts for 80% of these (2.4 mSv) (UNSCEAR, 2000 and IAEA, 2003), while the total annual effective dose due to inhalation and ingestion of terrestrial radionuclides is estimated to be 0.29 mSv , of which 0.17 mSv is attributable to ^{40}K and 0.12 mSv to the long-lived radionuclides in the ^{238}U and ^{323}Th series (UNSCEAR, 2000). A major concern in radiation safety is studying how ionizing radiation from naturally occurring radioactive materials affects humans, especially in places where these materials are found in large amounts (Souza et al., 2015). Therefore, the activity concentrations of the major primordial radionuclides in the soil, sediments, mine tailings, water and foodstuffs in gold mining regions should be measured in order to determine the level of gamma radiation exposure to miners and nearby residents, as mining activities are known to raise background gamma radiation levels by exposing NORMs to the surface according to UNSCEAR, (2000).

CHAPTER THREE: METHODS AND MATERIALS

3.1 Study areas and geological context

The study was conducted in three major artisanal and small-scale gold-mining regions of Uganda namely Namayingo 0.355189N, 33.844060E; Kassanda 0.546670N, 31.819719E; and Buhweju 0.3071N, 33.86552E. These districts represent some of the country's most active and geologically diverse gold-bearing terrains, each characterized by distinct lithological units, mineralization histories, and environmental conditions that influence the distribution of Naturally Occurring Radioactive Materials (NORMs). Buhweju gold mining area is located in Buhweju district in western Uganda, part of the Ankole sub-region. It is known for its ASGM mining activities, with gold deposits primarily found in riverine and alluvial environments, as well as in quartz vein-hosted formations (Nyakecho & Hagemann, 2014). Gold in Buhweju occurs in alluvial deposits spread along major rivers and streams, and also in banded iron formations and quartz veins within the Karagwe-Ankolean sedimentary rocks (Kaggwa et al., 2024). The presence of granitic pegmatites enriched in potassium feldspar and mica increases the likelihood of elevated natural radioactivity, while alluvial deposits may redistribute radioactive minerals through erosion, transport, and deposition.

Namayingo lies within the Busia greenstone belt, a region renowned for its Neoproterozoic rock formations, which are rich in gold deposits (Nyakecho & Hagemann, 2014). Gold mineralization in Namayingo (Nsango) is typically associated with quartz vein systems, shear zones, and weathered basement rocks. Mining activities in nearby areas date back to the early 20th century. Gold mining in Namayingo district, eastern Uganda, is predominantly artisanal and small-scale, involving manual excavation of gold-bearing rocks and alluvial deposits, often without formal licenses or regulatory oversight characterized by a recent gold rush following discoveries in villages such as Mpano 'A' and Nakudi. The mining activity has drawn hundreds of miners from across Uganda and neighboring countries, transforming subsistence farming communities into bustling mining hubs.

Gold mining in Kassanda district, Central Uganda, is primarily artisanal and small-scale (Kwagala et al., 2025), involving thousands of miners engaged in manual extraction of gold, often using rudimentary and hazardous methods. The district has a long history of gold mining dating back to the 1980s, with key mining areas including Kasita, Kagaba Hills, Bukuya, Kayonza, and Kitumbi.

Kassanda's mineralized zones commonly lie within weathered regolith and lateritic soils, which can accumulate radionuclides through geochemical concentration processes. The presence of potassic minerals and metamorphic rocks potentially contributes to variations in ^{238}U , ^{232}Th , and ^{40}K concentrations in soils and sediments. The choice of the selected gold processing areas is that they showed a potential for environmental contamination due to mining activities including milling, washing which generates a lot of waste that is disposed of into environment. Mining activities further disturb and redistribute these materials into soils, sediments, water sources, and agricultural fields.

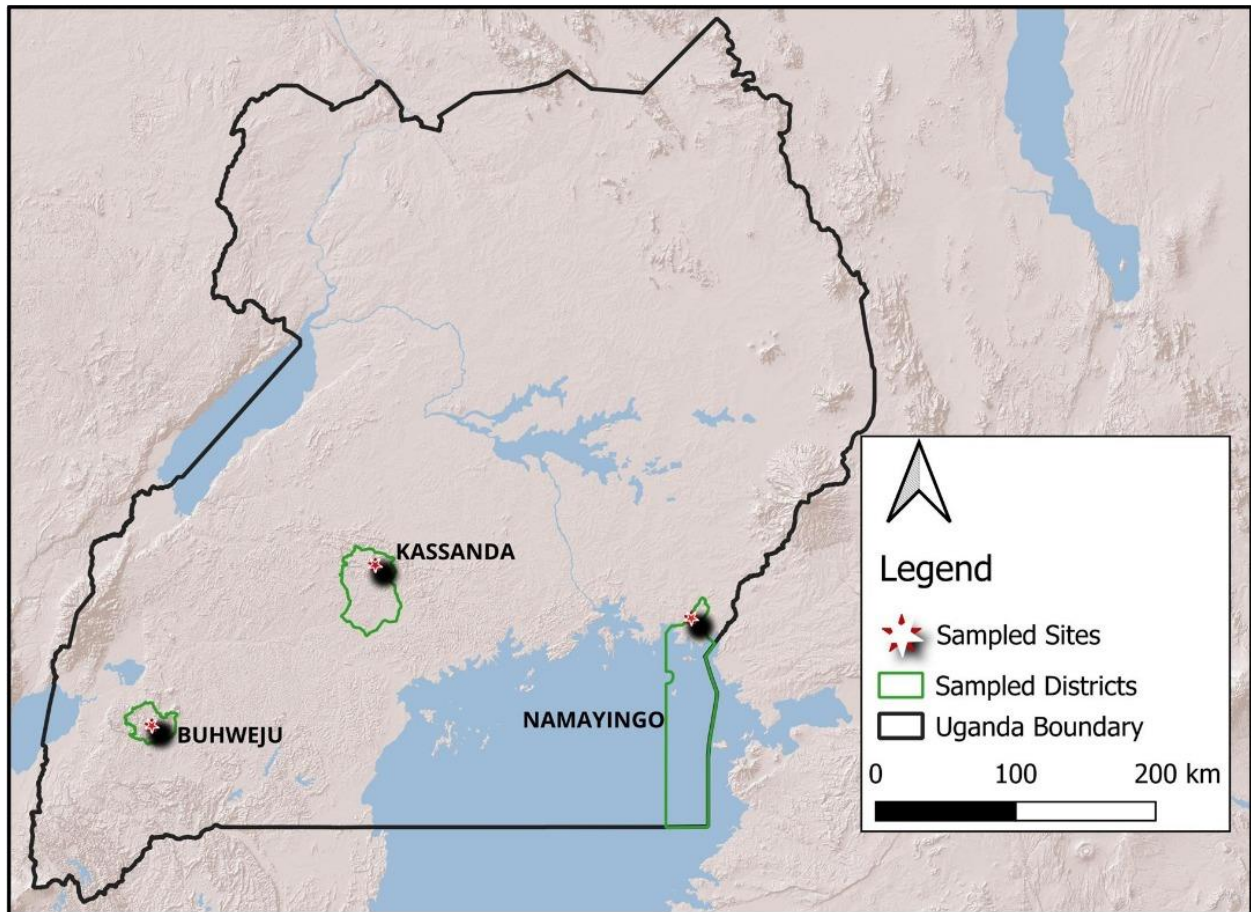


Figure 3. 1: map of Uganda showing study areas

3.2 Sampling

3.2.1 Soil sampling

Soil, sediments and tailings samples (500g) were collected using a stainless steel auger at defined depths, 0 to 30 cm along 10 m transects, as depth supports life, within 1 km of the gold mining area. This ensured a representative sampling of the soil layer where radionuclides may be concentrated or mixed due to agricultural and mining activities. To ensure statistical consistency of sampling, a transect sampling technique was used to select the sampling locations with some minor modifications, in compliance with IAEA principles. All vegetation, mulches, big stones, and debris were removed to expose the soil at each test site. The soil samples were collected at each sampling location, mixed uniformly, and then placed in Ziploc bags and were appropriately labeled and brought to the lab for examination. Soil and sediment samples were taken from 46 different places within the research regions (Fig. 3.2, 3.3, 3.4). Samples of soil were gathered from gardens where foodstuff samples were collected from, undeveloped areas surrounding mining sites, and mining sites themselves. Samples of sediments were collected from ponds and wetlands near the mining sites.



Figure 3. 2: Namayingo (Nsango) soil sampling site



Figure 3. 3: Kassanda soil sampling site

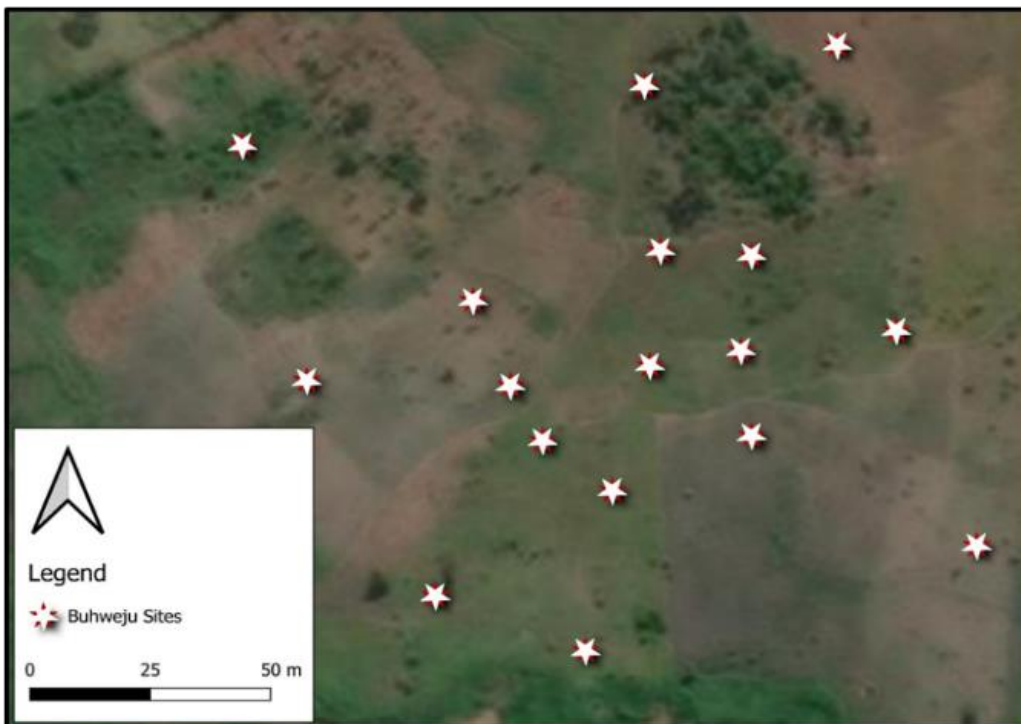


Figure 3. 4: Buhweju soil sampling sites

3.2.2 Foodstuff sampling

Food samples, alongside agricultural soils, were collected around the mining sites, food crops ($n=30$), including cassava tubers and tea leaves, were harvested within 1 km of mining areas. Mature cassava tubers (5) were uprooted, cleaned gently with water and sealed in zip-lock bags. Young tea leaves (6) were also collected from each plant and packed in air-tight bags. All samples were sealed, labeled with GPS coordinates, and transported at 4 °C to the laboratory.

3.2.3 Water sampling

Water samples were collected from three locations (upstream, midstream, and downstream) and mine waste waters found in the mining zones in triplicate using pre-cleaned glass bottles between 7 and 10 am. At each site, three water samples were taken by filling two-liter polypropylene containers with acid-washed samples. Before the final collection, each bottle was repeatedly washed with the sample water. To stop radionuclide adsorption onto container walls and suppress biological activity, the samples were acidified to $\text{pH} < 2$ as soon as possible after sampling using nitric acid (Madzivire et al., 2013 and IAEA, 2011). The samples were labeled, brought to the laboratory, and kept at 4 °C before analysis. Both the dissolved and suspended radionuclides were measured because the water samples had not been filtered before examination.

3.3 Sample preparation

Soil and sediment samples were prepared according to literature procedures with some as executed by Ivanova et al., (2001); Hu & Qi, (2013); Mihaylova et al., (2013). The foodstuff (cassava and tea) samples were prepared according to the reported method in the literature (Nguyen et al., 2023). The solid samples were oven dried at 100 °C for 24 hours, ground, and sieved through a 2 mm sieve to achieve homogeneity and packed into air tight bags as recommended by the IAEA (TRS No.295). The dried sample (0.2g) was weighed into digesting tubes, and moistened with some ultrapure water and the water sample (25 mL) was used for digestion. Subsequently, 69% nitric acid (6mL), 50v/v H_2O_2 (2mL) solution and 37% hydrochloric acid (6 mL) were added to the mixture and left to stand for 48hrs. The samples were then subjected to total digestion in the microwave model ETHOS UP, SN 19104530 at 200 °C in a fume hood for 18hrs and cooled to room temperature. After digestion, the residues were diluted with aqua regia of 3:1 HCl: HNO_3 (5ml). The sample extracts were transferred to a 50 mL PTFE volumetric flask and made to the mark with ultrapure water. An internal standard solution of each radionuclide ($100 \mu\text{g L}^{-1}$) was

added to each sample to correct for matrix interferences. Additionally, ^{40}K , ^{238}U and ^{232}Th standard solutions were used to calibrate the instrument, and reagent blanks using ultrapure water were also measured at intervals during the entire measurement process (Arogunjo et al., 2009).

Water samples were acidified using 1% nitric acid (HNO_3) to preserve the elements and reduce precipitation or adsorption losses. Water was filtered through a 0.45 μm pore size filter to remove suspended solids and particulates that can clog the nebulizer or affect ionization, then digested by microwave digestion with acids to fully dissolve elements into the solution (Hartwig et al., 2005).

3.4 Quantification of soil radioactivity

The in - situ radiation dose rates in μSvh^{-1} were measured at each soil sample collection point using a handheld portable GM counter (PRM-8000, S/N 80357, USA) with a nuclear detector to detect β -particles, γ - rays and x-rays around the gold processing and control sites, respectively. The global positioning system (GPS) was utilized to log the precise coordinates of every measurement location. The Geiger counter was positioned 1 meter above the ground (representing the height of human exposure) to accurately measure ambient radiation dose rates, thereby minimizing the impact of soil composition and surface contamination, and ensuring consistent and representative measurements at nine different locations, spaced 10 meters apart. Three measurements were taken at each sample collection point, and the mean was recorded for each point according to (Ogungbemi et al., 2023). Gamma dose rate in air was used for the description of terrestrial radiation, and expressed in nGyh^{-1} (IAEA-tecdoc, 2003). The counter readings were taken in microsieverts per hour and were converted to nanograys per hour using an appropriate conversion factor of ($1 \mu\text{Svhr}^{-1} = 1000 \text{nGyh}^{-1}$). These standards validate the idea that the sievert-to-gray conversion is 1:1 under normal gamma radiation weighting ($w_R=1$) and 3600s as expressed (Jamal & Abuqubu, 2016), using equation (3.1)

$$D_{\text{air}}(\text{nGyh}^{-1}) = D(\mu\text{Svhr}^{-1}) \times 0.27778 (\text{nGys}^{-1}) \times 3600s \dots\dots\dots(3.1)$$

Where $D_{\text{air}}(\text{nGyh}^{-1})$ is the absorbed gamma dose rate in air, $D(\mu\text{Svhr}^{-1})$ is the effective dose rate of radiation and $(0.27778 \text{nGys}^{-1} \times 3600s) = 1000 \text{nGyh}^{-1} = 1 \mu\text{Svh}^{-1}$

The instrument was calibrated according to the manufacturer's specifications and background radiation was measured at a control site before field measurements.

The result obtained was used to estimate the annual effective dose due to external exposure using equations (3.2) and (3.3) and excess lifetime cancer through equation (3.4) (Adel et al., 2022).

$$AED_{out} (mSvy^{-1}) = D_{air} (nGyh^{-1}) \times 0.2 \times 8760 (hy^{-1}) \times 0.7 (SvGy^{-1}) \times 10^{-6} (mSvnGy^{-1}) \dots \dots \dots (3.2)$$

$$AED_{in} (mSvy^{-1}) = D_{air} (nGyh^{-1}) \times 0.8 \times 8760 (hy^{-1}) \times 0.7 (SvGy^{-1}) \times 10^{-6} (mSvnGy^{-1}) \dots \dots \dots (3.3)$$

Where AED_{out} is the outdoor annual effective dose in $mSvy^{-1}$, D_{air} is the absorbed dose rate in $nGyh^{-1}$, the dose conversion factor of $0.7 SvGy^{-1}$ and the occupancy factor (OC) of 0.2 and 0.8 for outdoor and indoor exposures, respectively, through the exposure time 8760 h per year (UNSCEAR, 2017)

Excess lifetime cancer was calculated following equation (3.4) (Emad et al., 2022).

$$ELCR = AED_{out} \times DL \times RF \dots \dots \dots (3.4)$$

The calculation is based on the ICRP (International Commission of Radiation Protection), recommended outdoor annual effective dose (AED_{out}), life expectancy (DL, 70 years), and cancer risk factor (RF, $0.05 Sv^{-1}$).

3.5 Determination of radionuclide levels

This was done as described by Mazarakioti et al., (2022) where Inductively coupled plasma mass spectrometer (ICP-MS), (Thermo scientific, Serial Number: ICAP RQ03358). The instrument parameters nebulizer gas flow rates: 1.0044 l/min; auxiliary gas flow: 0.7947 l/min, ICP RF Power: 1548.6 W, pump speed: 40.0 rpm, and interface temperature: 30.26 °C. Data was acquired for the selected radionuclides (^{238}U , ^{232}Th and ^{40}K ,) using the quadrupole mass analyzer and MS detector. Using conversion factors, concentrations were converted from ppb to $Bqkg^{-1}$ according to IAEA, (2003) and He, (2011) 313 $Bqkg^{-1} / \%$ for ^{40}K (Abd El Rahman et al., 2022). Additionally, quality control checks (blanks and duplicates) were performed to ensure the accuracy and precision of the results.

3.6 Radiological hazard indices and human health risk assessment

Radiological hazard indices were calculated to assess the potential radiation risk that the study areas' population may face as a result of exposure to naturally occurring radionuclides present in the soil, sediment, foodstuffs and water. While human health risk assessment parameters were calculated to quantify the probability and severity of actual health effects or risks for the population on exposure for a specific period. The radiological parameters indices were determined from the

measured data. These radiological parameters used in this present study include absorbed dose rate, internal- radiation hazard index, and external-radiation hazard index, annual effective dose and excess lifetime cancer risk. These parameters have been established based on equations reported by (UNSCEAR, 2000) and have been used by various researchers Akpanowo et al., (2020), Dike et al., (2020) T. C et al., (2023) which have proved the reliability of these equations.

3.6.1 Absorbed dose rate

The quantity of radionuclides in the soil determines how much of the absorbed dose rate in air (D) is caused by natural radionuclides. Depending on the radionuclides present in the soil, the dose can be computed using absorbed dose rate conversion factors (Durusoy & Yildirim, 2017). The characteristic of external gamma radiation from terrestrial sources was determined by calculating the absorbed dose rate (D) in the air at a height of one meter above the ground. The following formula was used to determine the gamma absorbed dose rates after the conversion factors provided by UNSCEAR (2000) were adopted and computed by applying Equation (3.5) (Avwiri G.O, Ononugbo C.P, & Nwokeoji, 2014).

$$D \text{ (nGyh}^{-1}\text{)} = 0.462A_U + 0.604A_{Th} + 0.0417A_K \dots\dots\dots(3.5)$$

where the absorbed dose rate is denoted by D (nGy h⁻¹), 0.462, 0.662 and 0.0417 are the activity-to-dose conversion factors (nGyh⁻¹ per Bqkg⁻¹) for ²³⁸U, ²³²Th and ⁴⁰K, respectively according to UNSCEAR, European Commission and other researchers (UNSCEAR, 2008; UNSCEAR, 2017; Shi et al., 2024) and A_U, A_{Th}, and A_K are the activity concentrations (Bqkg⁻¹) of ²³⁸U, ²³²Th, and ⁴⁰K, respectively, in the soil sample, and D is the dose rate at 1 m above the ground (Durusoy & Yildirim, 2017). The allowable total absorbed dose rate for local workers should not exceed the worldwide average level of 57 nGyh⁻¹ (UNSCEAR, 2008b).

3.6.2 External and internal hazard index

The internal and the external radiation hazard indices are two of the radiological parameters calculated in this investigation. These parameters were developed using equations published by UNSCEAR (2000) and have been applied by several researchers (Adel et al., 2022; Shi et al., 2024) who have demonstrated the validity of using equations.

External hazards Index

H_{ex} represents the external hazard index, often known as the outside radiation hazard index. In soil samples, H_{ex} is frequently used to determine the radiation dose rate from external exposure to gamma radiation from naturally occurring radionuclides using equation (3.6) as used by (Joel et al., 2021).

$$H_{ex} = \frac{A_U}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \dots\dots\dots(3.6)$$

Where A_U , A_{Th} and A_K are the activity concentrations ($Bqkg^{-1}$) for ^{238}U , ^{232}Th and ^{40}K respectively. The value of this index should be less than 1.0, for the radiation hazard to be considered acceptable to the public (Ogungbemi et al., 2023).

Internal Hazard Index

Estimated by applying the equation (3.7) according to Joel et al., (2021)

$$H_{in} = \frac{A_U}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \dots\dots\dots(3.7)$$

Additionally, the H_{in} , which makes sure that the radiation's effective dose stays within the 1mSv/y limit (Pandit et al., 2020).

3.6.3 Annual Effective Dose

AED is defined as the radioactive coefficient used to judge the degree of impact of absorbed dose on health. The absorbed radiation dose rates were used to calculate the annual effective dose from gamma radiation exposures both indoor, IAED, and outdoor, OAED in mSv^{-1} and converted to Sv^{-1} by multiplying by 1000 ($1Sv = 1000 mSv$). Residents usually spend 80% of their time indoors and 20% of their time outdoors, according to UNSCEAR (2000) for the global population. As a result, the occupancy factors for radiation doses indoors and outdoors were established at 0.8 and 0.2, respectively. OEAD and IAED were computed using equations (8) and (9), respectively as used by Durusoy & Yildirim (2017) and Itodo et al., (2020) with a conversion factor of $0.7 Sv Gy^{-1}$ UNSCEAR, (2017), Turyahabwa et al., (2024) and Shi et al., (2024).

$$AED_{out} (mSvy^{-1}) = D_{air} (nGyh^{-1}) \times 0.2 \times 8760 (hy^{-1}) \times 0.7 (SvGy^{-1}) \times 10^{-6} (mSvnGy^{-1}) \dots \dots \dots (3.8)$$

$$AED_{in} (mSvy^{-1}) = D_{air} (nGyh^{-1}) \times 0.8 \times 8760 (hy^{-1}) \times 0.7 (SvGy^{-1}) \times 10^{-6} (mSvnGy^{-1}) \dots \dots \dots (3.9)$$

where AED (mSvy⁻¹) is the annual effective dose. D (nGyh⁻¹) is absorbed dose rate. The conversion factor (CF) is assigned a value of 0.7 SvGy⁻¹. T (h) is the annual exposure time of people outdoors (outdoor occupancy factor p = 0.2, T = 24×365×0.2 = 1752h) (UNSCEAR, 2008c).

3.6.4 Health risk assessment due to ingestion

3.6.4.1 Annual intake

The dose of a specific radionuclide that enters the body by digestion or inhalation within a year was calculated according to equation (3.10) (Alonso et al., 2006).

$$I = C \times CR \dots \dots \dots (3.10)$$

Where:

C = Activity concentration (Bqkg⁻¹ or BqL⁻¹)

CR = Consumption rate (kgy⁻¹ or Ly⁻¹)

3.6.4.2 The Annual Effective Dose (AED) Sv⁻¹

This expression was used to calculate the annual committed effective dose to an individual resulting from the intake of natural radionuclides (²³⁸U, ²³²Th, and ⁴⁰K) through the consumption of cassava, tea leaves and water in a specific environment (Hassan et al., 2021a; T. C et al., 2023). The annual effective dose from ingestion of food crops and water was estimated using equations (11) and (12) for the total yearly committed effective dose from the three natural radionuclides UNSCEAR, (2008b); Jibiri et al., (2007b).

$$AED_f (Svy^{-1}) = M (kgy^{-1}) (A_U D C_f U + A_{Th} D C_f Th + A_K D C_f K) \dots \dots \dots (3.11)$$

$$AED_w (Svy^{-1}) = M (Ly^{-1}) (A_U D C_f U + A_{Th} D C_f Th + A_K D C_f K) \dots \dots \dots (3.12)$$

Where the annual individual effective dose (Svy⁻¹) is represented by AED_f, the annual intake or consumption rate of a specific food crop (kgy⁻¹) and AED_w(Svy⁻¹) for water. M, annual intake of

radionuclides in cassava (170kgy^{-1}), tea (150kgy^{-1}) and water (730Ly^{-1}), A_U , A_{Th} , and A_K , the activity concentration in Bq/kg respectively (IAEA, 2016), and the ingestion dose conversion factor or coefficient (SvBq^{-1}) for radionuclides of interest by DC_f (i.e., DC_{fU} , DC_{fTh} , and DC_{fK}). For adults (≥ 17 years old), the DC_f values for ^{238}U , ^{232}Th , and ^{40}K are $4.5 \times 10^{-8} \text{SvBq}^{-1}$, $2.3 \times 10^{-7} \text{SvBq}^{-1}$, and $6.2 \times 10^{-9} \text{SvBq}^{-1}$, respectively (Ogungbemi et al., 2023; T. C et al., 2023).

3.6.4.3 Excess Lifetime Cancer Risk (ELCR)

Excess lifetime cancer risk (ELCR) was calculated using the following equation (3.13) according to the literature Fasanmi et al., (2021), Adel et al., (2022).

$$\text{ELCR} = \text{AED} \times \text{DL} \times \text{RF} \dots\dots\dots(3.13)$$

Where;

AED is the annual effective dose due to ingestion,

DL is the duration of life (70 years)

(RF) is the risk factor of 0.05Sv^{-1} which is fatal cancer risk per sievert.

The assumption that the lifetime average daily intake or exposure to NORMs is the same for 70 years. It is a carcinogenic potential that gives the probability of a population developing cancer due to exposure to low doses over a specific lifetime (Odelami et al., 2024).

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Radioactivity detection

The Fig 4.1, 4.2, and 4.3 below show the spatial distribution of ambient gamma dose rates ($\mu\text{Sv h}^{-1}$) across selected gold mining areas in Uganda. The maps are overlaid on a satellite image of a semi-vegetated landscape, showing sampling or measurement points represented by colored circles. The color scale (legend) at the top right ranges from green \rightarrow yellow \rightarrow orange \rightarrow red, corresponding to increasing gamma dose rate levels.

The impact of mining operations and regional environmental factors is evident in the geographical distribution of dose rates throughout the mining sites, which exhibits distinct variation. The core mining and ore-processing zone, where a number of locations are indicated in orange to red, has the highest dose rates. The accumulation of radionuclide-containing elements, including waste rock, crushed ore, and mine tailings, is probably the cause of these high readings. Naturally existing radionuclides are more exposed when mineralized strata are mechanically disturbed during excavation. Moderate dosage rates (yellow to light-green markers) are seen surrounding these high-dose locations. These zones are transitional areas where contaminated materials are partially dispersed by wind-borne fine particles, surface runoff, and human activities including small-scale farming. In contrast, lower dose rates (green markers) dominate the parts that are farther from active mining pits and tailings, and vegetated which reduces radionuclide exposure by shielding and dilution with uncontaminated material.

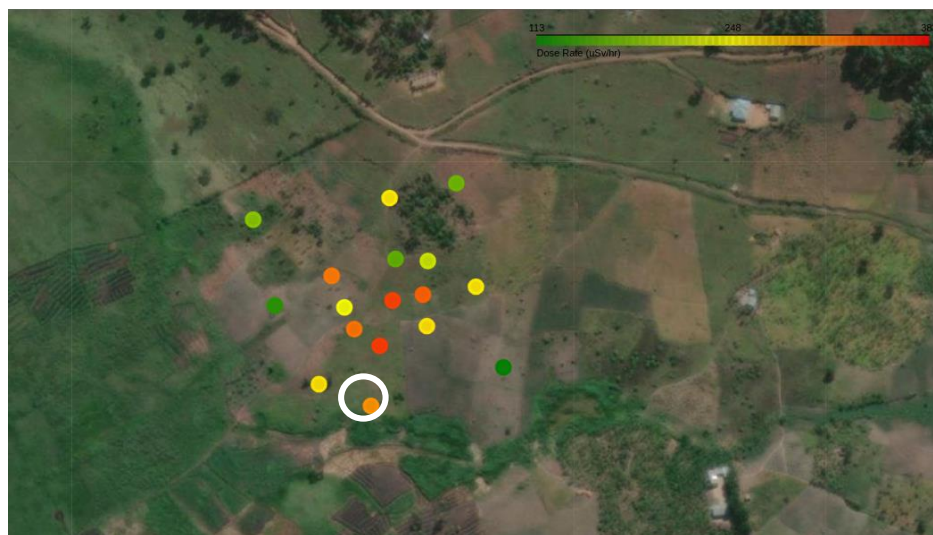


Figure 4. 1: Buhweju sampling or measurement site

Green points represent areas with relatively low dose rates ($\approx 113\text{--}180\ \mu\text{Svh}^{-1}$), indicating lower levels of radioactivity. Yellow to orange points indicate moderate dose rates ($\approx 180\text{--}280\ \mu\text{Svh}^{-1}$), suggesting some degree of radiological enhancement possibly due to soil mineralization, erosion of radioactive-bearing rocks, or anthropogenic disturbances. Red points highlight hotspot zones ($\approx 280\text{--}383\ \mu\text{Svh}^{-1}$), areas of elevated radiation likely linked to accumulation of uranium/thorium-bearing minerals, mine tailings, or secondary deposition of radionuclides.



Figure 4. 2: Kassanda sampling or measurement site

Green and light-yellow points dominate the peripheral parts of the area, reflecting lower radiation levels within the approximate background range ($113\text{--}180\ \mu\text{Svh}^{-1}$). Yellow to orange points appear clustered near the central section, indicating moderate dose rates ($180\text{--}280\ \mu\text{Svh}^{-1}$) possibly due to soil enrichment, or proximity to radiogenic sources. A distinct red point is visible at the center, marking the highest recorded dose rate ($383\ \mu\text{Svh}^{-1}$), suggesting a localized hotspot or elevated concentration of radioactive elements (e.g., U or Th-bearing minerals) due to accumulated mine tailings and soil disturbances.

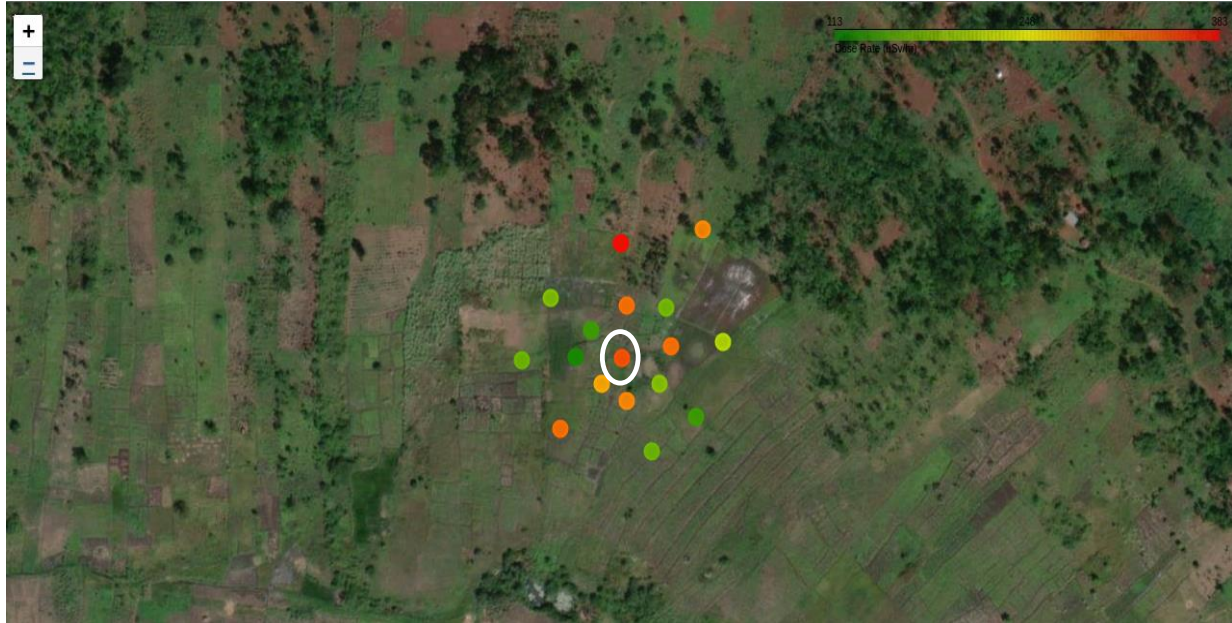


Figure 4. 3: Namayingo sampling or measurement site

Green markers represent low gamma dose rates ($\approx 110\text{--}180 \mu\text{Sv h}^{-1}$), reflecting normal background radiation levels likely influenced by natural soil and rock composition. Yellow and orange markers indicate moderate dose rates ($\approx 180\text{--}280 \mu\text{Sv h}^{-1}$), suggesting localized elevation possibly from natural mineralization or anthropogenic sources such as mining residues or soil disturbance. A single red marker near the northern-central section denotes the highest recorded dose rate ($\sim 383 \mu\text{Sv h}^{-1}$), implying a radiological hotspot possibly linked to concentrated mineralized materials, soil enrichment with uranium/thorium-bearing minerals, or proximity to artisanal mining activity.

Understanding this normally requires consideration of underlying geological features, which refers to the natural structures, formations, and materials that characterize the Earth's crust, including rock types, mineral compositions, landforms, and structural elements such as faults or folds. These features strongly influence environmental processes and the spatial distribution and mobility of naturally occurring radionuclides in upstream, midstream, and downstream areas.

Upstream

The elevated radionuclide levels observed in some upstream sampling points may be attributed to a combination of natural geological factors and indirect mining-related influences. In certain locations, upstream soils overlie geological formations naturally enriched with NORMs, particularly uranium-bearing granitic units, thorium-rich sands, and potassium-rich feldspathic

materials. Such natural variability can independently produce higher absorbed dose rates even in the absence of mining activities. Additionally, many artisanal gold mining regions contain legacy or abandoned upstream workings, including historic pits and weathered waste dumps that were never rehabilitated. These features may contribute to residual radioactive materials within the surrounding soils through long-term weathering. Atmospheric resuspension also may play a significant role, whereby fine particulates from tailings, exposed waste rock, and contaminated soils may be carried by wind and deposited upstream depending on seasonal wind patterns and turbulence. Consequently, the elevated dose-rate values observed upstream are more likely a result of natural geological enrichment combined with legacy or indirect mining influences, rather than hydrological transport alone. This highlights the complexity of radionuclide distribution within mining landscapes and underscores the need for integrated geological and environmental interpretation during radiological assessments.

Midstream

Across all three mapped sites, the midstream zones display a concentration of yellow, orange, and occasional red markers, representing moderately elevated to high external dose rates. This pattern highlights the continued influence of persistence of mining, sediment accumulation, human disturbance

Downstream

Downstream locations consistently show predominantly green and light-yellow markers, signifying low to moderately low external dose rates. The downstream decline in dose rates results from the dilution of contaminated sediments as they mix with cleaner sediments and organic matter, reducing the overall concentration of radioactive materials. Increasing distance from mining pits and ore processing, the supply of radionuclide-bearing particles sharply reduces, resulting in dose rates approaching natural background. Downstream areas often contain clay-rich soils, organic matter and vegetated floodplains that facilitate adsorption and immobilization of radionuclides, limiting their mobility and reducing surface exposure levels. The downstream regions tend to be more stable due to reduced soil disturbance, with intact vegetation cover and minimal human activity. This allows radionuclides to remain bound within sediments rather than being re-exposed at the soil surface.

Table 5.1 (appendix), shows the results of the absorbed dose rate in μSvhr^{-1} measured at 1 m above the ground caused by NORMs in the soil and the associated radiological hazard indices. These included, gamma absorbed dose rate (nGyh^{-1}), outdoor and indoor annual effective dose rate (mSvy^{-1}) and lifetime cancer risk which were determined using equations 3.1, 3.2, 3.3 and 3.4, respectively. The average absorbed dose rate ranged between 0.241 to 0.251 μSvh^{-1} which are marginally below the global average of 0.274 μSvh^{-1} UNSCEAR, (2008). The average outdoor and indoor effective dose ranged from 0.295 to 0.308 mSvy^{-1} and 1.181 to 1.23 mSvy^{-1} which are higher than the global average around 0.07 mSvy^{-1} for outdoors and 0.34 mSvy^{-1} for indoors respectively, according to UNSCEAR and other studies. The worldwide average annual effective dose from both outdoor and indoor sources is about 0.48 mSvy^{-1} as recommended by UNSCEAR report. The higher absorbed and annual effective dose rate values may be due to high radionuclides concentrations of ^{238}U , ^{232}Th and ^{40}K and their decay products which are widely spread in soil and rocks of the earth's crust within the gold mining sites. When naturally occurring deep buried rocks are excavated and crushed into various sizes, radionuclides associated with them are redistributed (Ugbede & Echeweozo, 2017), and this has the capability of enhancing the radiation level within the gold mining sites. According to Enyinna & Onwuka (2014), the geological and geophysical parameters of the environment primarily determine these radionuclides and the radiation they emit. The implication of this is that the probability of one developing cancer over a life time in the gold mining environment is very high. Hence calls for determination of radionuclide levels in soils. Other researchers including Moshupya et al., (2022) and Odelami et al., (2024) have also done similar studies and obtained higher absorbed dose rate compared to the recommended maximum value of 59 nGyh^{-1} .

4.2 Average radioactivity levels

Using conversion factors suggested by IAEA tec doc no.1363 (IAEA, 2003), the elemental levels of uranium (ppm), thorium (ppm), and potassium (%) were computed into Bq/kg. These are 1 ppm = 12.35 Bqkg^{-1} of ^{238}U ; and 1 ppm is = 4.06 Bqkg^{-1} of ^{232}Th , 1% K = 313 Bqkg^{-1} of ^{40}K . These have been applied in previous studies, including Bajoga et al., (2019); and Abd El Rahman et al., (2022).

4.2.1 The radionuclide levels in soil and sediments

The average activity concentrations of ^{238}U , ^{232}Th , and ^{40}K (Bqkg^{-1}) were determined using ICP-MS for different soil and sediment samples collected from selected gold mining areas in Uganda, as shown in Fig. 4.4, 4.5 and 4.6 below.

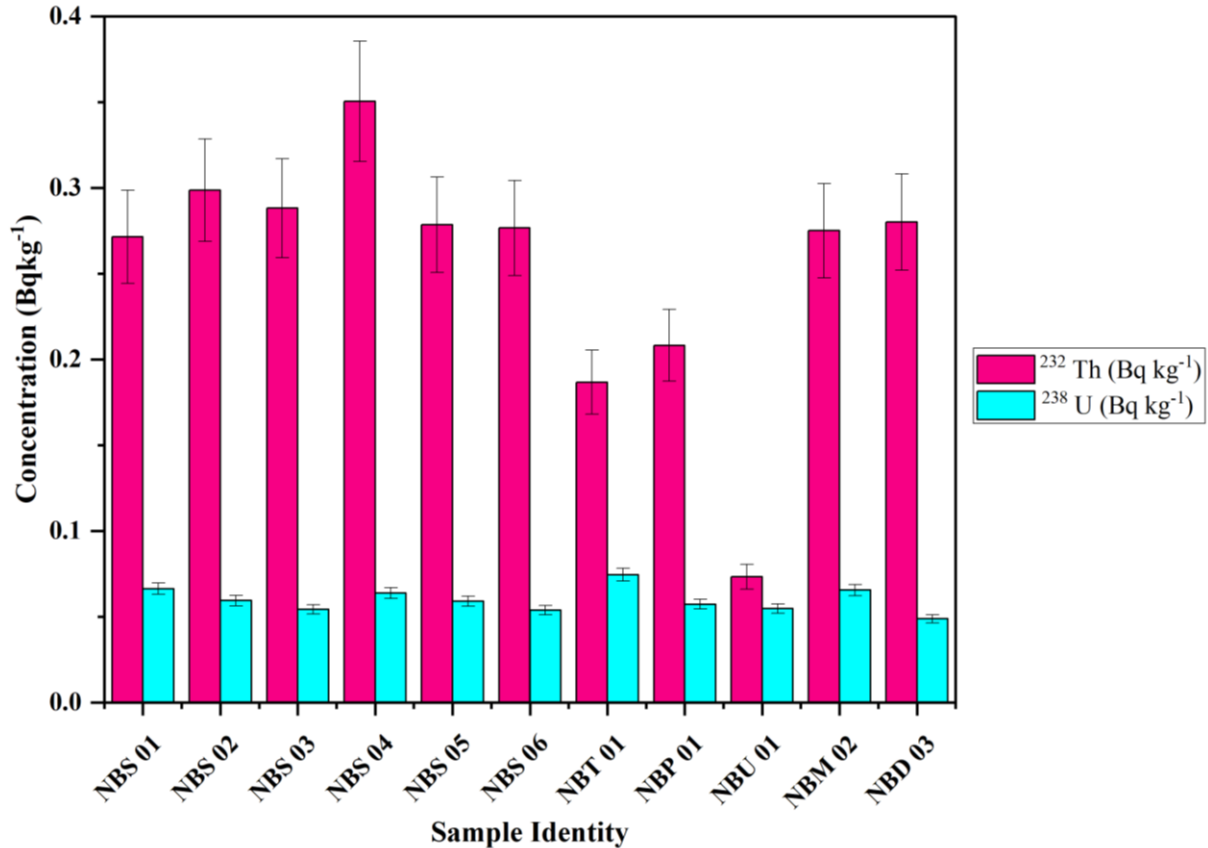


Figure 4. 4: The radionuclide levels of the ^{238}U and ^{232}Th in soil and sediments from the Namayingo gold mining site

Thorium enrichment characterizes the activity concentrations of ^{232}Th and ^{238}U in the evaluated soil samples across the research region. In every sampling location, the concentrations of ^{232}Th are consistently higher than those of ^{238}U ; with NBD 04 having the highest ^{232}Th value, indicating localized geological enrichment that is probably related to Th-bearing minerals such monazite within the parent lithology. As a result of uranium's enhanced mobility under tropical weathering conditions, which facilitates leaching and movement from the soil matrix, ^{238}U levels, remain consistently low ($0.04 - 0.07 \text{ Bqkg}^{-1}$). The significant amount of immobile thorium within reactive mineral stages and advanced chemical weathering is evidenced by the consistently high

Th:U ratios in all samples. The radionuclide levels of ^{238}U , ^{232}Th and ^{40}K were below the global limits as those reported by other researchers from other parts of the world (Faanu et al., 2011).

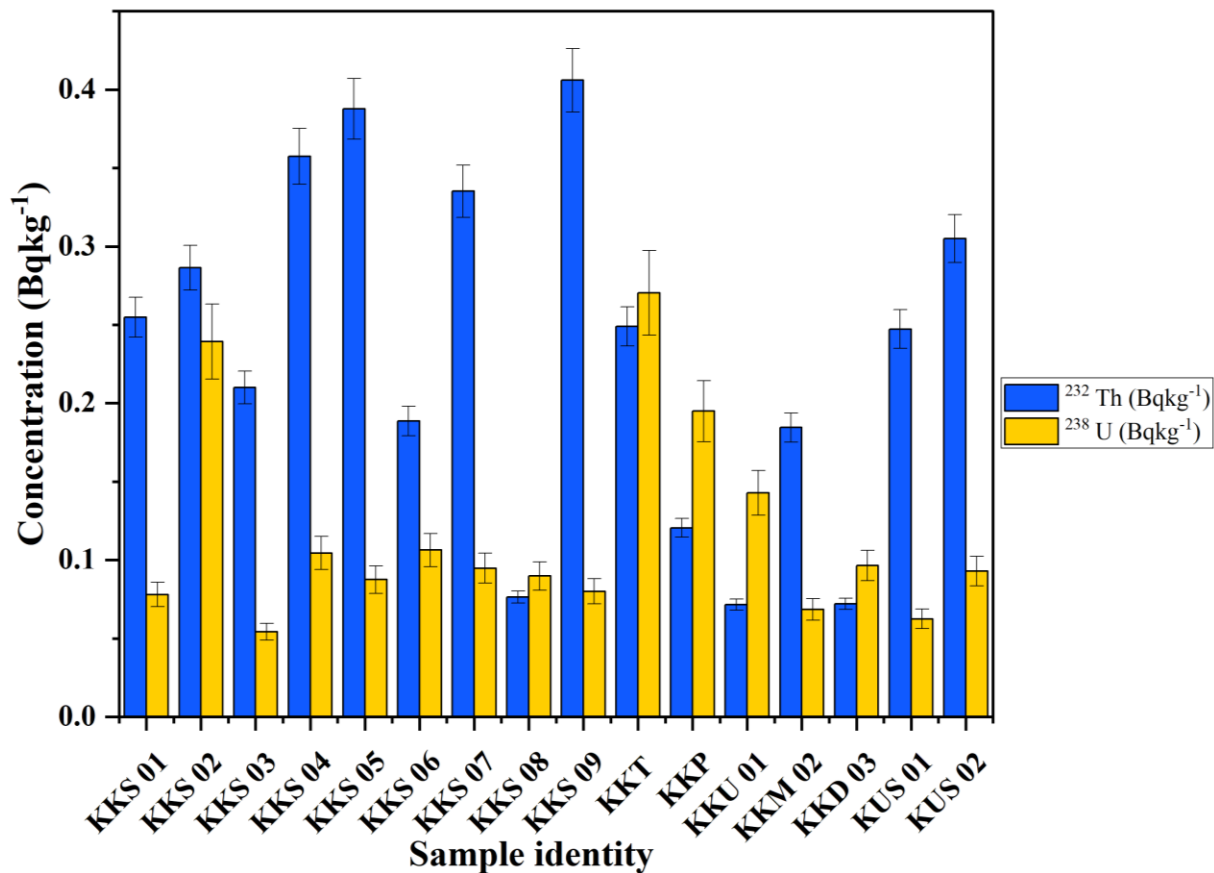


Figure 4. 5: The radionuclide levels of the ^{238}U and ^{232}Th in soil and sediments from the Kassanda gold mining site.

The radionuclides levels of ^{232}Th and ^{238}U across the sampled gold-mining sites exhibit distinct geographic fluctuations that are a result of both the influence of mining activities and geological controls. Overall, ^{232}Th radioactivity levels are consistently higher than those of ^{238}U in all samples. The predominance of thorium indicates that the underlying geology of the research locations has more Th-bearing minerals, such as thorite or monazite. The typical hosts of gold mineralization in Uganda include granitic and metamorphic terrains, which are frequently linked to these minerals.

In contrast, ^{238}U concentrations, which range from 0.05 to 0.27 Bqkg $^{-1}$, are comparatively low at all sampling locations. Sample KKT (mine tailings), has the greatest uranium concentrations. Given its mobility in oxidizing settings and relatively lower quantities, uranium may eventually

leak from surface soils. Tropical weathering, which tends to mobilize U more preferentially than Th, is consistent with this geochemical tendency.

The conclusion of extensive weathering and the predominance of refractory Th-bearing minerals is further supported by the samples' consistently high Th/U ratios. The detected levels for both radionuclides remain well below the worldwide average soil values (UNSCEAR), indicating minimal radiological influence from these elements at the current level of mining activities.

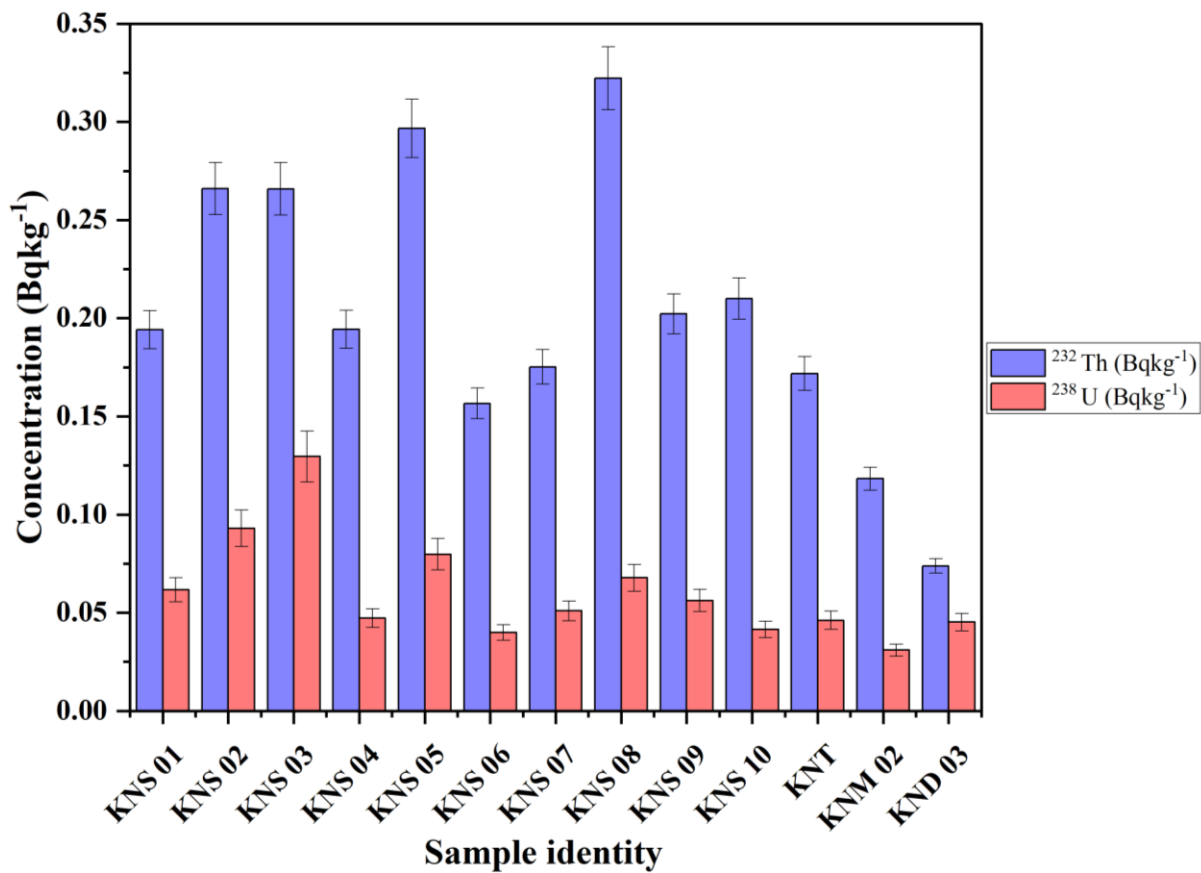


Figure 4. 6: The radionuclide levels of the ^{238}U and ^{232}Th in soil and sediments from the Buhweju gold mining site

The research area's soil and sediment samples exhibit distinct geographic variability in the levels of ^{232}Th and ^{238}U , which represent both surface geochemical processes and the geological framework. With prominent peaks at KNS 05 and KNS 08, the levels of ^{232}Th are consistently higher than those of ^{238}U across all sampling points, suggesting localized enrichment probably related to Th-bearing accessory minerals like monazite within the gold-bearing lithologies.

Conversely, ^{238}U levels are consistently low, ranging from roughly 0.03 to 0.13 Bqkg^{-1} , with slightly higher values in KNS.

Table 5.4 (appendix), show the summary of average radionuclide levels for soil and sediment samples from the selected gold mining areas which ranged from 0.0568 to 0.1024 Bqkg^{-1} for ^{238}U , 0.1177 to 0.2778 Bqkg^{-1} for ^{232}Th , and 5.2E-06 to 8.5E-06 Bqkg^{-1} for ^{40}K . The analysis revealed that the mean activity concentrations of the radionuclides followed a decreasing trend in the sequence $^{40}\text{K} > ^{238}\text{U} > ^{232}\text{Th}$. When compared with international reference levels, the average concentrations were generally below the worldwide recommended values of 35 Bqkg^{-1} for ^{238}U , 30 Bqkg^{-1} for ^{232}Th and 400 Bqkg^{-1} for ^{40}K (UNSCEAR, 2000).

4.2.2 Average radionuclide levels in foodstuffs (Bqkg^{-1}) within gold mining areas

Table 4.1 summarizes the average radionuclide levels of ^{238}U , ^{232}Th , and ^{40}K (Bqkg^{-1}) in foodstuffs samples from the gold mine sites. The average radionuclide levels in cassava tubers for ^{238}U were $0.0193 \pm 0.00023 \text{ Bqkg}^{-1}$ and $0.01134 \pm 0.00028 \text{ Bqkg}^{-1}$, while those of ^{232}Th were $0.038 \pm 2.542\text{E-}05 \text{ Bqkg}^{-1}$ and $0.037 \pm 0.00008 \text{ Bqkg}^{-1}$, respectively, for the Namayingo and Kassanda gold mining areas. The levels of ^{40}K were $8.9\text{E-}05 \pm 5.4\text{E-}07 \text{ Bqkg}^{-1}$ and $8.1\text{E-}05 \pm 1.2\text{E-}06 \text{ Bqkg}^{-1}$, respectively. These values were all below the world average values of 35 Bqkg^{-1} , 30 Bqkg^{-1} and 400 Bqkg^{-1} for ^{238}U , ^{232}Th and ^{40}K respectively. Because an intake of natural ^{40}K does not produce an effective dosage, the mean AED_{ing} values were derived using the amounts of ^{238}U and ^{232}Th in the food crop samples. Whereas $0.015 \pm 0.00026 \text{ Bqkg}^{-1}$, $0.037 \pm 0.00004 \text{ Bqkg}^{-1}$, $9\text{E-}05 \pm 7.124\text{E-}07 \text{ Bqkg}^{-1}$ for U, Th, K in tea from Buhweju. All AED results were below the allowable limits of 1mSv^{-1} recommended by United Nations Scientific Committee on the Effects of Atomic Radiation, indicating that the food crops are safe to eat and do not pose any radiological health hazards despite the anthropogenic activities in the research regions.

Table 4. 1: Average radionuclide levels in cassava tubers and tea leaves (Bqkg^{-1})

Location	^{238}U (Bqkg^{-1})	^{232}Th (Bqkg^{-1})	^{40}K (Bqkg^{-1})
Namayingo	0.0193	0.038	8.91E-05
Kassanda	0.014	0.037	8.09E-05
Buhweju	0.015	0.037	9.08E-05

A comparable study on assessment of radionuclides levels in soil and cassava food crop from solid mineral mining site in Ishiagu, Ivo L.G.A of Ebonyi State, Nigeria, reported 12.37, 16.08 and 144.29 for are ^{226}Ra (^{238}U), ^{232}Th and ^{40}K respectively lower than 35, 30 and 400 world average (Mgbeokwere et al., 2021). In another study, the significant mean activity concentrations of the radionuclides ^{40}K , ^{226}Ra (^{238}U), and ^{232}Th were found in the Pottery regions, camp 1, and camp 2 varied from 193.68 to 300.92 Bqkg⁻¹, 23.03 to 37.24 Bqkg⁻¹, and 135.33 to 158.43 Bqkg⁻¹, respectively. The estimated total mean annual effective dosage of 2.03 mSvy⁻¹ from exposure to these three detected radionuclides is concerning. This amount surpasses the 1 mSvy⁻¹ recommended limit, suggesting possible health hazards related to the radioactive contamination from cassava intake in this area. In conclusion, the study reveals that samples of cassava from the studied location showed high levels of radiotoxicity, which raises questions regarding the safety of eating cassava from this area (Amakom et al., 2023).

4.2.3 Average radionuclide levels in water within the gold mining areas.

Table 4.2 shows the radionuclide levels for water samples from selected gold mining areas. The values ranged from 0.0001 to 0.00898, approximately 0.035 and 5.32E-06 to 8.97E-06 for ^{238}U , ^{232}Th and ^{40}K , respectively. Based on available literature, the world average radionuclide levels in water are roughly between 0.4 to 0.6 BqL⁻¹, 0.66 to 0.78 BqL⁻¹, and 4.14 to 5.87 BqL⁻¹, for ^{238}U , ^{232}Th , and ^{40}K though these can vary widely based on local geology. These values were within safety limits set by WHO (Herschey, 2012).

Table 4. 2: Average radionuclide levels in water

Location	^{238}U (BqL ⁻¹)	^{232}Th (BqL ⁻¹)	^{40}K (BqL ⁻¹)
Namayingo	0.00898	0.03541	8.97E-06
Kassanda	0.00236	0.03551	1.14E-05
Buhweju	0.00021	0.03568	5.32E-06
world average	35	30	400

4.2.4 The low radioactivity levels of potassium 40

The relatively low levels of radioactivity from Potassium 40 observed across all the selected gold-mining areas mainly due to geological factors. Gold mineralization in these regions mostly occurs in quartz veins, quartz–carbonate veins, and silicified shear zones. Quartz lacks potassium, and the widespread silicification linked with hydrothermal gold deposits replaces the original K-bearing

minerals, such as feldspars and biotite, with silica. This process of alteration causes a gradual decrease in potassium, which further decreases the levels of ^{40}K in nearby soils, tailings, and sediments. The relatively low K activity in comparison to the U- and Th-series radionuclides found in the studied ambient matrices can be explained by the geological setting favoring enrichment of uranium- and thorium-bearing accessory minerals rather than potassium.

Geologically, the low K levels result from gold mineralization in these Ugandan belts being hosted in quartz-rich, potassium-poor historic rocks where K-bearing minerals are destroyed by hydrothermal precipitation, favoring quartz and sulphide formations free of potassium. Beyond geology, potassium availability is further reduced by severe tropical weathering, rainfall-driven leaching, topsoil stripping, and dilution by quartz-rich tailings, which leads to low K activity in environmental matrices.

4.3 The estimation of potential radiological hazards

To estimate the risk due to radiation exposure from radionuclides in the soil, sediment foodstuffs and water, a radiological risk assessment was conducted for the various sample locations.

4.3.1 Radiological hazards due to radionuclides' activity levels in soil and sediment

Radiological hazard assessment was determined from radionuclide levels of ^{238}U , ^{232}Th and ^{40}K of the soil and sediment samples. Radioactivity in soil caused the calculated absorbed dose in air (specific absorbed dose rate in air outdoors) in units of nGyh^{-1} per Bqkg^{-1} . For environmental gamma dose from NORMs in soil, the UNSCEAR, (2000) report provides widely used conversion coefficients to link Bqkg^{-1} to nGyh^{-1} ; 0.462, 0.604, 0.0417 for ^{238}U , ^{232}Th , ^{40}K respectively and have been applied in other publications including Durusoy & Yildirim, (2017); Hasson et al., (2022) and Shi et al., (2024). To determine annual effective dose rate, the outdoor (0.2) or indoor (0.8) occupancy factors were used. In addition, the factor (0.7 SvGy^{-1}) was used to change $D(\text{nGyh}^{-1})$ into $\text{AED}_{\text{total}} (\text{mSvy}^{-1})$, which is usually acquired by the human body according to (UNSCEAR, 2000).

The radiological hazard parameters, including absorbed dose rate (D), annual effective dose (IAED and OAED), internal (H_{in}) and external (H_{ex}) hazard indices, and excess lifetime cancer risk (ELCR) were evaluated in three selected gold mining areas: Namayingo, Kassanda, and Buhweju.

Table 4.3 provides average values of radiological hazard parameters from soil and sediment samples in gold mining regions. These parameters are used to evaluate potential radiation exposure to humans and the environment, based on measured radionuclide activity concentrations. The assessment is supported by mean values, facilitating systematic comparisons between sampling sites and established global reference limits regarding NORM-related mining disturbances.

Table 4. 3: Average values for the radiological hazard parameters for NORMs in soil and sediment samples

Parameter	LOCATIONS			Safety Limit / Reference
	Namayingo	Kassanda	Buhweju	
Dose rate, D (nGy h ⁻¹)	0.1041 ± 0.021	0.128 ± 0.041	0.0925 ± 0.028	Global avg. 59 nGyh ⁻¹ (UNSCEAR, 2000)
IAED (mSv y ⁻¹)	0.00048	0.00063	0.00045	1 mSv y ⁻¹ (ICRP, 2007)
OAED (mSv y ⁻¹)	0.00013	0.00020	0.00011	1 mSv y ⁻¹ (ICRP, 2007)
Hin	0.0008	0.0011	0.0007	≤1 (safe)
Hex	0.00065	0.00079	0.00060	≤1 (safe)
ELCR (×10 ⁻⁶)	2.23	2.75	1.99	Typical global ~290 ×10 ⁻⁶

Dose Absorption Rate (D)

Gamma radiation from naturally occurring radionuclides in the air is measured by the absorbed dose rates. After Namayingo and Buhweju, Kassanda had the greatest dosage rate (0.128 nGy h⁻¹). In comparison to the global average 59 nGyh⁻¹ UNSCEAR report, 2000, all readings are incredibly low, indicating minimal exposure danger. The discrepancies are probably due to variations in the mineral composition and local geology.

Annual Effective Dose

Kassanda once more displayed the highest values for both the internal (IAED) and external (OAED) yearly effective dosages, which were extremely low. These doses are significantly lower than the ICRP's 2007 suggested 1 mSv y^{-1} limit, indicating that there is no harm to one's health from ingesting or external exposure. The dosage rate patterns are consistent with slight variations between locations.

Radiation hazard indices (Hex and Hin)

Natural radionuclides in soil do not present serious radiological risks in the areas under study, as evidenced by the fact that both the internal (Hin) and external (Hex) hazard indices were far below the safe threshold of 1. Kassanda's somewhat greater dosage rate is consistent with its slightly higher indices.

Lifetime Risk of Cancer (ELCR)

The ELCR values ($1.99\text{--}2.75 \times 10^{-1}$) were incredibly low, suggesting a very little lifetime cancer risk from exposure to natural radionuclides. Given its greater dose and hazard index values, Kassanda was found to be at the highest danger.

All three gold mining regions have extremely low exposure levels overall, according to the radiological hazard assessment, indicating that there are no urgent health risks for the local populace. The somewhat higher readings in Kassanda could be the result of mining operations or localized natural radionuclide enrichment brought on by geological conditions.

Identifying any seasonal or temporal variations in radioactive concentrations, periodic monitoring is advised, especially in Kassanda. Additionally, determination of origins, mobility, and potential for bioaccumulation in soil, water, and food, targeted studies should be carried out in regions exhibiting increased values. Some related studies Ibrahim, U., Akpa, T. C., & Daniel, (2013), Olufunmbi et al., (2016) have been conducted, and lower radioactivity levels in soil and sediments have been reported compared to these studies.

4.3.2 Radiological hazards due to ingestion of foodstuffs and water

The radiological dangers associated with the intake of products and drinking water contaminated with naturally occurring radioactive materials (NORMs) in the research area were presented in

Table 4.4. The assessment is based on measured activity concentrations of relevant radionuclides and the corresponding ingested dose estimations for distinct exposure paths. These findings support the interpretation of the potential health effects of radionuclide transfer through the food chain by offering insight into the possible internal radiation exposure to the local population resulting from dietary intake and water consumption. They also enable comparison with internationally recommended safety limits.

Table 4. 4: Average value for the radiological health hazard parameters for NORMs in foodstuffs

Sample ID	Annual intake (Bqy ⁻¹)	AED (mSvy ⁻¹)	ELCR
NCU 01	33.160 ± 0.039	1.051E-06	3.68E-06
NCM 02	35.871 ± 0.317	1.076E-06	3.77E-06
NCD 03	56.805± 0.373	1.319E-06	4.62E-06
KCU 01	40.177 ± 0.224	1.140E-06	3.99E-06
KCM 02	35.871 ± 0.317	1.068E-06	3.74E-06
KCD 03	36.058 ± 0.091	1.084E-06	3.79E-06
MC 01	35.692 ± 0.150	1.121E-06	3.92E-06
BTU 01	37.731 ± 0.148	3.733E-09	1.31E-08
BTM 02	40.870 ± 0.307	3.854E-09	1.35E-08
BTD 03	36.261 ± 0.071	3.807E-09	1.33E-08

The annual intake values for the food samples ranged (33.16–56.81 Bqy⁻¹) showed moderate variation across sites, with the highest value at NCD 03, suggesting slightly elevated radionuclide uptake in that area. The corresponding Annual Effective Dose values (1.05E-06–1.32E-06 Svy⁻¹) are all far below the ICRP 1 mSvy⁻¹ public exposure limit, indicating no immediate radiological concern from food consumption in the studied districts. Similarly, ELCR values remain within acceptable international risk ranges (10⁻⁶–10⁻⁴). Overall, the findings suggest that while some areas show slightly higher radionuclide intake, the radiological risk from consuming these food crops poses no radioactive risk; however, ongoing surveillance in higher-intake zones is advised.

4.3.3 Radiological hazards due to ingestion of water

The table shows the estimated annual intake of radionuclides (Bq y^{-1}), the corresponding total annual effective dose (AED) in $\mu\text{Sv y}^{-1}$, and the excess lifetime cancer risk (ELCR) for populations in selected gold-mining areas, namely Namayingo, Kassanda, and Buhweju. These parameters are estimated based on the consumption of water and indicate potential radiological exposure to humans in these regions.

Table 4. 5: Average values the radiological health hazard parameter for NORMs in water

Location	Annual Intake (Bqy^{-1})	Total AED (μSvy^{-1})	ELCR
Namayingo	58.637	0.00005	0.00017
Kassanda	53.569	0.00004	0.00015
Buhweju	52.305	0.00004	0.00015

According to the findings, Namayingo has the highest yearly intake (58.637 Bq y^{-1}) and total AED ($0.00005 \mu\text{Sv y}^{-1}$), closely followed by Kassanda and Buhweju. The ELCR values, which range from 0.00015 to 0.00017 for all three sites, are extremely low, indicating that the lifetime risk of cancer from radionuclide consumption in these communities is negligible and much below international safety guidelines. Overall, these results suggest that, despite the presence of radionuclides in the gold-mining environment, the potential risk to one's health from ingesting is minimal under the current exposure levels.

4.4 Potassium 40 analysis using ICP-MS

The determination of concentration of K-40 was below the detection limits using ICP-MS due to majorly two major interferences: (a) Determining K-40 in environmental samples is difficult because only 0.0117% of natural potassium is radioactive, producing weak gamma emissions that are often close to background noise. Potassium is mobile in the environment and accurate detection requires long counting times and (b) elemental isobaric interferences (Russell et al., 2022) at mass 40 since Argon gas from the plasma has a mass to charge ratio (m/z) of 40, the same as for K-40 which created a major isobaric interference making direct detection of K-40, $m/z = 40$ complicated in standard ICP-MS (Anneliese Lust, 1998). Mathematical interference correction was used in determining the concentration of K-40 (interfering isotope) by use of an equation. By measuring the concentration of total potassium via K-39 (with a highest natural abundance of 93.26% and non-interfering isotope), the concentration of K-40 was determined using its natural abundance

(multiplying by 0.000117) (UNSCEAR, 2000). However, its levels remained below the detection limit.

4.5 Control site findings

Control sites showed no significant difference in radionuclide concentrations, with values within natural background ranges. This was evidenced by descriptive data trends, which demonstrate that mining locations exhibit higher concentrations while control-site values continuously fall within global natural background ranges. This suggested that gold-mining operations have little effect on these non-mining areas and that they are essentially unaltered. The low and consistent values verify that the chosen control sites were appropriate and that the analytical techniques were effective in separating background levels from contamination resulting from mining. Artisanal gold mining appears to be the main cause of elevated NORM levels in the study region, as evidenced by the stark difference between the elevated concentrations found in mining sites and the negligible control-site values. Overall, the negligible control-site results show that residents outside of mining zones are not at risk from radiation and offer a trustworthy baseline for analyzing differences within the research region.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Surface soil, sediments, water and food crops samples collected from the selected artisanal gold mining sites in Uganda were assessed for their radiological contents using ICP-MS technique. The average absorbed dose rates (0.241–0.251 μSvhr^{-1}) in the study areas were slightly below the global average of 0.274 μSvhr^{-1} . The activity concentrations of ^{238}U , ^{232}Th , and ^{40}K in soil, sediment, water, and food crops were lower than worldwide averages and within recommended safety limits, indicating minimal radiological risk to local populations. Higher levels of ^{238}U and ^{232}Th compared to ^{40}K were observed across all sites. The variations in radionuclide concentrations may be attributed to geological composition, mineralization, and mining-related activities. This study provides important baseline data for future radiological monitoring in Uganda's gold mining areas. Despite localized elevation, the overall absorbed dose rates (0.241–0.251 μSvhr^{-1}) were below the UNSCEAR global average, indicating normal background radiation levels. The calculated Annual Effective Dose (AED) values for ingestion and external exposure were significantly below the ICRP public dose limit of 1 mSvyr^{-1} , indicating extremely low exposure risk. While radioactive hazard indices (H_{ex} , $H_{\text{in}} < 1$) confirmed negligible radiation danger from ambient elements, annual intake and the consequent Excess Lifetime Cancer Risk (ELCR) values fell within the permitted worldwide safety limit of 10^{-4} – 10^{-6} .

This research provides a critical baseline for radiological surveillance in Uganda's mining regions and contributes to national efforts under NDP IV to ensure sustainable natural resource utilization, environmental protection, and strengthened regulatory oversight.

5.2 Recommendations

Although the current study provided important baseline data on the radioactivity levels, annual intake and radiological health risks associated with naturally occurring radionuclides in selected ASGM areas of Uganda, the results revealed a number of gaps and limitations. Resolving these issues is crucial to enhancing future evaluations and improving public health and environmental protection.

Sites with elevated radionuclide levels identified under Objective 1 should be prioritized for further study to ascertain their sources, environmental mobility potential for bioaccumulation and there is a need to determine transfer factors (TF). These investigations will support effective risk management and remediation strategies in gold mining regions.

For the evaluated radionuclides, the study found low radioactivity levels and annual consumption values for the assessed radionuclides, which were all below international reference limits. However, the results are constrained by the restricted range of radionuclides analysed, with an emphasis mainly on ^{238}U , ^{232}Th and ^{40}K . Important alpha-emitting radionuclides that frequently dominate ingestion dosage even at low activity concentrations, such as ^{226}Ra , ^{228}Ra , and ^{210}Po , were not assessed. Therefore, these radionuclides should be included in future research to provide a more thorough evaluation of the radiological dosage associated with ingestion.

Future studies should include long-term and seasonal sampling to capture variations in mining activity, hydrology, and agriculture, ensuring that worst-case exposure scenarios are adequately represented.

Radiological risk assessments should integrate ingestion, inhalation, and external gamma exposure pathways to provide a more comprehensive evaluation of total population dose and health risk.

Strict regulation and mandatory treatment of mine tailings and wastewater before environmental discharge should be emphasized.

Addressing these limitations through extended radionuclide analysis, more dietary data collection, seasonal monitoring and multi-pathway exposure assessment will enhance the reliability of future radiological health risk evaluations in gold-mining environments.

5.3 Limitations of the study

Restricted geographical coverage. The study may not accurately reflect all of Uganda's gold-mining regions because it was limited to specific gold-mining locations. Radionuclide levels may be impacted by regional differences in mining techniques and geology.

Seasonal and temporal constraints. Because sampling was limited to the dry season, the results only reflect baseline dry-season conditions and do not account for potential seasonal fluctuations in radionuclide mobility and concentrations that may arise during the wet season as a result of increased leaching and runoff. As a result, possible peak exposure levels after heavy rains can be overestimated.

Limited sample size. Although sufficient for a first evaluation, the quantity of samples examined might not fully capture the micro-scale differences in the distribution of radionuclides within each mining site.

Focused only on specific radionuclides. The study mainly evaluated naturally existing radionuclides (^{238}U , ^{232}Th and ^{40}K). Due to resource and technical limitations, measurements of radon gas and other potentially significant radionuclides were not made.

Inadequate evaluation of long-term exposure. The study does not assess cumulative or long-term exposure effects on the population; instead, it offers a snapshot of present radiological conditions.

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APPENDICES
Areas Visited



Appendix 1: Collecting data on mining methods and waste disposal.



Appendix 2: Waste water flows to the wetland through the garden in Kassanda gold mining area.



Appendix 3: Waste water from the gold processing site flowing through the cassava garden in Namayingo



Appendix 4: showing proximity of tea garden in open space to the processing site in Buhweju gold mining area

Tables of raw results

Appendix 5: Absorbed dose rate and radiological parameters in soil

Sample id	Longitude	Latitude	D (ngyh ⁻¹)	OAED (msvy ⁻¹)	IAED (msvy ⁻¹)	ELCR
NS2501	33.82176	0.35396	173.33	0.213	0.850	0.744
NS2502	33.82191	0.35455	310.00	0.380	1.521	1.331
NS2503	33.82221	0.35436	323.33	0.397	1.586	1.388
NS2504	33.82192	0.35400	377.33	0.463	1.851	1.620
NS2505	33.82167	0.35464	143.33	0.176	0.703	0.615
NS2506	33.82160	0.35390	180.00	0.221	0.883	0.773
NS2507	33.82214	0.35471	293.33	0.360	1.439	1.259
NS2508	33.82153	0.35442	323.33	0.397	1.586	1.388
NS2509	33.82207	0.35386	310.00	0.380	1.521	1.331
NS2510	33.82209	0.35462	170.00	0.208	0.834	0.730
NS2511	33.82138	0.35430	183.33	0.225	0.899	0.787
NS2512	33.82173	0.35367	143.33	0.176	0.703	0.615
NS2513	33.82218	0.35400	323.33	0.397	1.586	1.388
NS2514	33.82142	0.35453	206.67	0.253	1.014	0.887
NS2515	33.82188	0.35379	123.33	0.151	0.605	0.529
NS2516	33.82132	0.35404	170.00	0.208	0.834	0.730
NS2517	33.82160	0.35377	340.00	0.417	1.668	1.459
KS2501	31.78964	0.69755	330.00	0.405	1.619	1.416
KS2502	31.78976	0.69784	340.00	0.417	1.668	1.459
KS2503	31.78919	0.69703	210.00	0.258	1.030	0.901
KS2504	31.78929	0.69756	120.00	0.147	0.589	0.515
KS2505	31.78987	0.69753	286.67	0.352	1.406	1.230
KS2506	31.78997	0.69767	240.00	0.294	1.177	1.030
KS2507	31.78989	0.69704	173.33	0.213	0.850	0.744
KS2508	31.78999	0.69690	103.33	0.127	0.507	0.444
KS2509	31.78946	0.69720	316.67	0.388	1.553	1.359
KS2510	31.78967	0.69676	313.33	0.384	1.537	1.345

KS2511	31.78981	0.69726	280.00	0.343	1.374	1.202
KS2512	31.78996	0.69728	200.00	0.245	0.981	0.858
KS2513	31.78934	0.69733	303.33	0.372	1.488	1.302
KS2514	31.78962	0.69708	253.33	0.311	1.243	1.087
KS2515	31.78912	0.69734	213.33	0.262	1.047	0.916
KS2516	31.78948	0.69750	180.00	0.221	0.883	0.773
KS2517	31.78962	0.69731	383.33	0.470	1.880	1.645
BS2501	30.35442	-0.34111	220.00	0.270	1.079	0.944
BS2502	30.35416	-0.34158	170.00	0.208	0.834	0.730
BS2503	30.35423	-0.34133	163.33	0.200	0.801	0.701
BS2504	30.35458	-0.34069	260.00	0.319	1.275	1.116
BS2505	30.35383	-0.34179	320.00	0.392	1.570	1.374
BS2506	30.35390	-0.34120	186.67	0.229	0.916	0.801
BS2507	30.35397	-0.34137	323.33	0.397	1.586	1.388
BS2508	30.35411	-0.34190	263.33	0.323	1.292	1.130
BS2509	30.35442	-0.34147	353.33	0.433	1.733	1.517
BS2510	30.35347	-0.34089	306.67	0.376	1.504	1.316
BS2511	30.35422	-0.34077	263.33	0.323	1.292	1.130
BS2512	30.35359	-0.34136	113.33	0.139	0.556	0.486
BS2513	30.35484	-0.34169	333.33	0.409	1.635	1.431
BS2514	30.35425	-0.34110	260.00	0.319	1.275	1.116
BS2515	30.35469	-0.34126	243.33	0.298	1.194	1.044
BS2516	30.35440	-0.34130	133.33	0.164	0.654	0.572
BS2517	30.35403	-0.34148	350.00	0.429	1.717	1.502

Appendix 6: Radioactivity levels for NORMs in soil and sediment samples, foodstuffs and water from the selected areas

Sample matrix	Radionuclides	Namayingo	Kassanda	Buhweju	World average
Soil and sediment	²³⁸ U (Bqkg ⁻¹)	0.0584	0.0601	0.0568	33
	²³² Th (Bqkg ⁻¹)	0.1204	0.1253	0.1177	45
	⁴⁰ K (Bqkg ⁻¹)	5.187 E-06	5.147 E-06	5.941 E-06	420
Foodstuff	²³⁸ U (Bqkg ⁻¹)	0.0193	0.014	0.015	NA
	²³² Th (Bqkg ⁻¹)	0.038	0.037	0.037	NA
	⁴⁰ K (Bqkg ⁻¹)	8.91E-05	8.09E-05	9.08E-05	NA
Water	²³⁸ U (BqL ⁻¹)	0.00898	0.0023	0.00021	35
	²³² Th (BqL ⁻¹)	0.03541	0.0355	0.0356	30
	⁴⁰ K (BqL ⁻¹)	8.97E-06	1.14E-05	5.32E-06	400

Appendix 7: The radionuclide levels of the ^{238}U , ^{40}K and ^{232}Th in soil and sediments, food stuffs and water samples from selected gold mining sites.

Sample Identity	Sample mass /mg	^{238}U /ppb	^{232}Th (ppb)	^{40}K /ppb
NBS 01	200.436 + 0.054	5.344 + 0.034	33.105 + 0.450	0.459 + 0.008
NBS 02	201.718 + 0.029	4.781 + 0.085	36.407 + 0.297	0.468 + 0.003
NBS 03	208.415 + 0.023	4.385 + 0.081	35.124 + 0.100	0.467 + 0.009
NBS 04	201.808 + 0.020	5.135 + 0.119	42.809 + 0.392	0.028 + 0.000
NBS 05	203.214 + 0.020	4.744 + 0.183	33.908+ 0.175	0.849 + 0.007
NBS 06	201.308 + 0.020	4.351 + 0.090	33.702 + 0.176	0.625 + 0.005
NBT 01	203.410 + 0.017	6.013 + 0.035	22.720 + 0.180	0.220 + 0.001
NBP 01	200.808 + 0.017	4.618 + 0.060	25.364 + 0.089	0.371 + 0.003
NBU 01	202.283 + 1.060	4.423 + 0.048	202.367 + 0.939	0.545 + 0.004
NBM 02	208.229 + 0.280	5.277 + 0.097	33.519 + 0.115	0.440 + 0.006
NBD 03	206.546 + 0.201	3.914 + 0.076	34.159 + 0.024	0.726 + 0.010
KKS 01	201.700 + 0.162	6.293 + 0.138	31.049 + 0.222	0.789 + 0.008
KKS 02	203.596 + 0.166	19.292 + 0.205	34.876 + 0.141	1.185 + 0.022
KKS 03	208.533 + 0.180	0.004 + 0.001	25.587 + 0.252	0.729 + 0.008
KKS 04	213.533 + 0.180	8.434 + 0.061	43.610 + 0.085	0.989 + 0.026
KKS 05	213.138 + 0.130	7.054 + 0.058	47.287 + 0.389	0.773 + 0.008
KKS 06	202.917 + 0.161	8.570 + 0.266	23.021 + 0.096	0.564 + 0.006
KKS 07	203.833 + 0.180	7.647 + 0.307	40.822 + 0.238	0.039 + 0.059
KKS 08	205.296 + 0.166	7.273 + 0.176	9.307 + 0.012	2.903 + 0.024
KKT	207.138 + 0.130	6.446 + 0.092	49.527 + 0.292	1.027 + 0.037
KKT	201.796 + 0.166	21.786 + 0.398	30.394 + 0.177	0.455 + 0.008
KKU	211.633 + 0.180	11.516 + 0.167	8.738 + 0.004	0.942 + 0.021
KKM	210.033 + 0.180	7.788 + 0.102	22.478 + 0.105	0.715 + 0.000
KKD 03	214.833 + 0.180	5.530 + 0.040	33.506 + 0.122	0.105 + 0.002
KKP	207.533 + 0.180	15.721 + 0.199	14.686 + 0.070	0.280 + 0.008
KNS 01	202.533 + 0.180	4.975 + 0.163	23.669 + 0.125	0.199 + 0.001
KNS 02	214.104 + 0.160	7.499 + 0.157	32.434 + 0.188	0.369 + 0.003
KNS 03	205.533 + 0.180	10.446 + 0.084	32.333 + 0.300	0.655 + 0.007
KNS 04	205.196 + 0.166	3.807 + 0.050	23.756 + 0.179	0.408 + 0.005
KNS 05	203.104 + 0.160	6.435 + 0.095	36.210 + 0.136	0.452 + 0.004
KNS 06	203.296 + 0.166	3.223 + 0.050	19.091 + 0.048	0.292 + 0.004
KNS 07	208.396 + 0.166	4.122 + 0.147	21.361 + 0.060	0.165 + 0.003
KNS 08	217.104 + 0.160	5.458 + 0.088	39.312 + 0.115	0.475 + 0.005
KNS 09	200.288 + 0.176	4.533 + 0.093	24.655 + 0.128	0.373 + 0.007
KNS 10	200.996 + 0.166	3.349 + 0.040	25.612 + 0.133	0.225 + 0.004
KNT	200.896 + 0.166	3.722 + 0.112	20.999 + 0.239	0.175 + 0.001
KUS 01	201.896 + 0.166	5.035 + 0.109	30.170 + 0.232	0.025 + 0.000
KUS 02	206.288 + 0.176	4.881 + 0.116	37.190 + 0.151	0.293 + 0.004
KNM 01	203.996 + 0.166	2.496 + 0.032	14.414 + 0.068	0.073 + 0.002
KND 03	205.496 + 0.166	3.643 + 0.121	9.007 + 0.003	0.042 + 0.002
MCS 01	201.896 + 0.166	8.261 + 0.289	67.747 + 0.457	0.271 + 0.003
NCU 01	212.596 + 0.166	0.729 + 0.004	8.853 + 0.003	2.730 + 0.007
NCM 02	2.730 + 0.007	0.946 + 0.010	8.949 + 0.002	2.845 + 0.018
NCD 03	209.596 + 0.166	3.000 + 0.042	9.882 + 0.013	2.964 + 0.027
KCU 01	211.896 + 0.166	1.369 + 0.023	9.262 + 0.013	2.917 + 0.032
KCM 02	203.596 + 0.166	1.037 + 0.035	8.827 + 0.000	2.816 + 0.044
KCD 03	205.396 + 0.166	1.010 + 0.010	8.979 + 0.004	2.017 + 0.035
MC 01	204.596 + 0.166	0.823 + 0.013	9.415 + 0.019	2.792 + 0.013
BTU 01	207.096 + 0.166	1.195 + 0.016	8.971 + 0.006	2.725 + 0.040
BTM 02	210.033 + 0.180	1.511 + 0.032	9.065 + 0.007	2.949 + 0.028
BTD 03	200.854 + 0.202	0.933 + 0.014	9.276 + 0.020	3.030 + 0.000

KNUW 01	0.0018 + 0.0005	8.7623 + 0.0025	0.0886 + 0.0018
KNMW 02	0.0166 + 0.0017	8.6518 + 0.0293	0.0611 + 0.0006
KNDW 03	0.0186 + 0.0005	8.6565 + 0.0010	0.0990 + 0.0007
KNPW 04	0.0298 + 0.0017	8.7359 + 0.0024	0.4313 + 0.0064
NBUW 01	1.3687 + 0.0076	8.6320 + 0.0007	0.2481 + 0.0029
NBMW 02	1.1041 + 0.0113	8.6426 + 0.0021	0.2344 + 0.0038
NBDW 03	0.5840 + 0.0047	8.6343 + 0.0005	0.2386 + 0.0037
NBPW 04	0.0050 + 0.0000	8.6327 + 0.0013	0.4246 + 0.0059
KKUW 01	0.0173 + 0.0015	8.6283 + 0.0005	0.2103 + 0.0011
KKMW 02	0.0189 + 0.0008	8.6283 + 0.0005	0.0077 + 0.0001
KKDW 03	0.3444 + 0.0057	8.6573 + 0.0017	0.0127 + 0.0003
KKPW 04	0.3800 + 0.0062	8.7263 + 0.0079	1.2312 + 0.0186
MCW 05	0.0081 + 0.0008	8.6287 + 0.0005	0.1741 + 0.0021
