DOCTORAL (PhD) DISSERTATION

Survey of Naturally Occurring Radionuclides in Soils, Water, and Rice from Artisanal and Small-Scale Gold Mining Affected Areas in Ghana

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

AAPM – American Association of Physicists in Medicine

ADR – Adsorption Desorption Recovery (heap-leach facility unit)

ANL – Argonne National Laboratory

ANOVA – Analysis of Variance

ASTM – American Society for Testing and Materials

BGO – Bismuth Germanate

Bq – Becquerel

CR_w – Water-to-Rice Concentration Ratio

DMP – Department of Mines and Petroleum

DNA – Deoxyribonucleic Acid

DOE – Department of Energy

ELCR – Excess Lifetime Cancer Risk

GBC – Ghana Broadcasting Corporation

GCR – Galactic Cosmic Rays

GDP – Gross Domestic Product

GOLDBOD – Ghana Gold Board

GSA – Ghana Standards Authority

Gy – Gray

HPGe – High-Purity Germanium

IAEA – International Atomic Energy Agency

ICRP – International Commission on Radiological Protection

INFOSAN – International Food Safety Authorities Network

IQR – Interquartile Range

IT – Isomeric Transition (nuclear decay mode)

IMF – International Monetary Fund

L – Litre

LNT – Linear No-Threshold (model)

LN_2 – Liquid Nitrogen

MDA – Minimum Detectable Activity

MeV – Mega-electron Volt

MoFA – Ministry of Food and Agriculture (Ghana)

mSv – Millisievert

NCRP – National Council on Radiation Protection and Measurements

NDT – Non-Destructive Testing

NORM – Naturally Occurring Radioactive Material

pH – Potential of Hydrogen

PIPS – Passivated Implanted Planar Silicon

ppm – Parts per million

RNA – Ribonucleic Acid

Ra_{eq} – Radium Equivalent Activity

ROI – Region of Interest

SCR – Solar Cosmic Rays

SDD – Silicon Drift Detector

TAEC – Tanzania Atomic Energy Commission

TDS – Total Dissolved Solids

TF – Transfer Factor

UNSCEAR – United Nations Scientific Committee on the Effects of Atomic Radiation

WHO – World Health Organization

ABSTRACT

The study surveys the distribution and radiological health implications of naturally occurring radionuclides of ^{238}U, ^{226}Ra, ^{232}Th, ^{228}Th, and ^{40}K in various media including soils, heap pad soils, surface waters, boreholes and/or hand-dug wells, and rice cultivated in unregulated artisanal and small-scale gold mining communities in Ghana. The study applied high-purity Germanium (HPGe) gamma spectrometry and gross alpha/beta screening using PIPS detectors to determine activity concentrations and assess associated risks through the following avenues: external exposure, water ingestion, and the dietary intake of rice. The mean activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in soils were determined to be 24±3 Bq/kg, 25±3 Bq/kg, and 328±63 Bq/kg, with maximum values of 87, 72, and 1168 Bq/kg, respectively, exceeding UNSCEAR (2000) averages in some cases. Hazard indices were within safety thresholds with Ra_{eq} of 85±12 Bq/kg; absorbed dose rate of 40±6 nGy/h; and annual effective dose of 0.05±0.01 mSv/y, although hotspots were observed. Heap pad soils showed lower values between 11–29 Bq/kg for ^{238}U and ^{232}Th; 213–236 Bq/kg for ^{40}K with absorbed dose rates of 30–32 nGy/h, Ra_{eq} concentration of 66–70 Bq/kg, gamma index, external hazard index and internal hazard index below 1, and annual effective doses of 0.15–0.16 mSv/y, all below limits for reuse in construction. Surface water samples presented the highest risk, with mean concentrations of 1.15±0.21 Bq/L for ^{226}Ra, 1.60±0.35 Bq/L for ^{228}Th, and 20.70±3.60 Bq/L for ^{40}K. The committed effective dose averaged 0.41±0.08 mSv/y (range 0.06–1.64 mSv/y), four times the WHO guideline of 0.1 mSv/y. Excess lifetime cancer risk (ELCR) averaged 1.59×10^{-3}, with maxima of 6.30×10^{-3}. However, borehole and well samples, screened for gross alpha and beta were within GSA and WHO guidelines. Rice samples recorded mean concentrations of 5.03±1.75 Bq/kg for ^{226}Ra, 1.76±0.57 Bq/kg for ^{232}Th, and for ^{40}K, 39.10±10.12 Bq/kg with maximums of 10.63, 3.80, and 63.88 Bq/kg. Though these present no or low radiological health risk, there is an indication of uptake of ^{40}K from soil and radium isotopes from water. Although average total doses ($\leq$ 1 mSv/y) remained within ICRP (2007) limits, exceedances in water ingestion doses and ELCR values highlight potential long-term risks. The study provides critical baseline data for Ghana and underscores the need for strengthened monitoring, remediation, and regulatory oversight in mining-affected communities.

KIVONAT

A tanulmány a természetes eredetű radionuklidok (^{238}U, ^{226}Ra, ^{232}Th, ^{228}Th és ^{40}K) eloszlását és sugár-egészségügyi hatásait vizsgálja különböző közegekben, többek között talajokban, cianidos zagytároló talajokban, felszíni vizekben, fúrt kutakban és/vagy ásott kutakban, valamint rizsben, amelyet szabályozatlan, kis- és kézműves aranybányászati közösségekben termesztenek Ghánában. A vizsgálat nagy tisztaságú germánium (HPGe) gamma-spektrometriát, valamint PIPS-detektorokkal végzett összesített alfa/béta-szűrést alkalmazott az aktivitáskoncentrációk meghatározására és a kapcsolódó kockázatok értékelésére az alábbi útvonalakon keresztül: külső expozíció, vízbevitel és a rizs étrendi fogyasztása. A talajban mért ^{238}U, ^{232}Th és ^{40}K átlagos aktivitáskoncentrációi rendre 24±3 Bq/kg, 25±3 Bq/kg és 328±63 Bq/kg voltak, a maximális értékek pedig 87, 72 és 1168 Bq/kg, amelyek egyes esetekben meghaladják az UNSCEAR (2000) átlagait. A veszélyességi mutatók a biztonsági küszöbértékeken belül voltak: Ra_{eq} = 85±12 Bq/kg; elnyelt dózisintenzitás = 40±6 nGy/h; éves effektív dózis = 0,05±0,01 mSv/év, bár forrópontok előfordultak. A cianidos zagytároló talajok alacsonyabb értékeket mutattak: 11–29 Bq/kg a ^{238}U és ^{232}Th esetében, valamint 213–236 Bq/kg a ^{40}K esetében, az elnyelt dózisintenzitás 30–32 nGy/h, Ra_{eq} = 66–70 Bq/kg, a gamma-index, a külső és belső veszélyességi indexek 1 alatt maradtak, míg az éves effektív dózis 0,15–0,16 mSv/év, vagyis a határértékek alatt az építési újrafelhasználás szempontjából. A felszíni vízminták mutatták a legnagyobb kockázatot: az átlagos koncentrációk ^{226}Ra-ra 1,15±0,21 Bq/L, ^{228}Th-re 1,60±0,35 Bq/L, és ^{40}K-ra 20,70±3,60 Bq/L voltak. A felvett effektív dózis átlaga 0,41±0,08 mSv/év (tartomány: 0,06–1,64 mSv/év), ami négyszerese a WHO 0,1 mSv/év irányelvének. Az élettartamra vetített rákkockázat (ELCR) átlaga $1{,}59\times10^{-3}$ volt, maximuma pedig $6{,}30\times10^{-3}$. Ugyanakkor a fúrt és ásott kutakból származó minták, amelyeket összes alfa- és béta-aktivitásra vizsgáltak, a GSA és WHO irányelveinek megfelelőek voltak. A rizsminták átlagos aktivitáskoncentrációi ^{226}Ra-ra 5,03±1,75 Bq/kg, ^{232}Th-re 1,76±0,57 Bq/kg és ^{40}K-ra 39,10±10,12 Bq/kg értékeket mutattak, a maximális értékek pedig 10,63, 3,80 és 63,88 Bq/kg voltak. Bár ezek nem vagy csak alacsony sugáregészségügyi kockázatot jelentenek, kimutatható a ^{40}K talajból és a rádium izotópok vízből történő felvétele. Bár az átlagos teljes dózis (≤ 1 mSv/év) az ICRP (2007) határértékein belül maradt, a vízbevitelből származó dózisok és az ELCR értékek túllépése potenciális hosszú távú kockázatokra utal. A tanulmány alapvető

bázisadatokat szolgáltat Ghána számára, és hangsúlyozza a bányászat által érintett közösségekben a megerősített monitorozás, kármentesítés és szabályozási felügyelet szükségességét.

RÉSUMÉ

L'étude examine la distribution et les implications radiologiques pour la santé des radionucléides d'origine naturelle ^{238}U, ^{226}Ra, ^{232}Th, ^{228}Th et ^{40}K dans divers milieux, y compris les sols, les sols de lixiviation, les eaux de surface, les forages et/ou les puits traditionnels, ainsi que le riz cultivé dans des communautés minières artisanales et à petite échelle non réglementées au Ghana. L'étude a appliqué la spectrométrie gamma au germanium de haute pureté (HPGe) et le dépistage global alpha/bêta à l'aide de détecteurs PIPS pour déterminer les concentrations d'activité et évaluer les risques associés par les voies suivantes : exposition externe, ingestion d'eau et consommation alimentaire de riz. Les concentrations d'activité moyennes de ^{238}U, ^{232}Th et ^{40}K dans les sols étaient respectivement de 24±3 Bq/kg, 25±3 Bq/kg et 328±63 Bq/kg, avec des valeurs maximales de 87, 72 et 1168 Bq/kg, dépassant dans certains cas les moyennes de l'UNSCEAR (2000). Les indices de risque se situaient dans les seuils de sécurité avec un Ra_{eq} de 85±12 Bq/kg ; un débit de dose absorbée de 40±6 nGy/h ; et une dose efficace annuelle de 0,05±0,01 mSv/an, bien que des points chauds aient été observés. Les sols de lixiviation présentaient des valeurs plus faibles entre 11–29 Bq/kg pour ^{238}U et ^{232}Th ; 213–236 Bq/kg pour ^{40}K, avec des débits de dose absorbée de 30–32 nGy/h, des Ra_{eq} de 66–70 Bq/kg, un indice gamma, un indice de risque externe et interne inférieurs à 1, et des doses efficaces annuelles de 0,15–0,16 mSv/an, toutes en dessous des limites pour une réutilisation dans la construction. Les échantillons d'eau de surface présentaient le risque le plus élevé, avec des concentrations moyennes de 1,15±0,21 Bq/L pour ^{226}Ra, 1,60±0,35 Bq/L pour ^{228}Th et 20,70±3,60 Bq/L pour ^{40}K. La dose efficace engagée moyenne était de 0,41±0,08 mSv/an (plage : 0,06–1,64 mSv/an), soit quatre fois la directive de l'OMS de 0,1 mSv/an. Le risque de cancer à vie excédentaire (ELCR) moyen était de $1,59\times10^{-3}$, avec des maximas de $6,30\times10^{-3}$. Toutefois, les échantillons de forages et de puits, testés pour l'activité alpha et bêta globale, étaient conformes aux directives de la GSA et de WHO. Les échantillons de riz ont enregistré des concentrations moyennes de 5,03±1,75 Bq/kg pour ^{226}Ra, 1,76±0,57 Bq/kg pour ^{232}Th et 39,10±10,12 Bq/kg pour ^{40}K, avec des valeurs maximales de 10,63, 3,80 et 63,88 Bq/kg. Bien que ceux-ci ne présentent aucun ou faible risque radiologique pour la santé, une indication d'absorption de ^{40}K à partir du sol et d'isotopes du radium à partir de l'eau est observée. Bien que les doses totales moyennes (≤ 1 mSv/an) soient restées dans les limites de l'ICRP (2007), les dépassements des doses liées à l'ingestion d'eau et des valeurs d'ELCR soulignent des risques à long terme. L'étude fournit des

données de référence essentielles pour le Ghana et souligne la nécessité d'un renforcement de la surveillance, de la remédiation et du contrôle réglementaire dans les communautés affectées par l'exploitation minière.

INTRODUCTION

1.1. Background

All of us are surrounded by natural background radiation. The level of background radiation varies depending on the activity concentration of naturally occurring radionuclides present in air, soil, plants, water, and building materials, and it also varies from one place to the other over time.

Terrestrial-origin materials comprise of some naturally occurring radionuclides of which uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K) are significant to radiation protection. Natural radioactivity is the primary source of population dose (ICRP, 1991, 2007; UNSCEAR, 2000). The activity level of these radionuclides is largely affected by the geological conditions and the rock type in the soil, leading to different concentrations at different locations (Faanu et al., 2016a, 2016b; Uosif, 2007; Xinwei et al., 2006). Anthropogenic activities such as mining (minerals, oil and gas), and processing of mine minerals has the potential tendency of increasing the concentration of these radionuclides (IAEA, 2005; UNSCEAR, 2000). The main contributors of external gamma radiation exposures are the decay products from naturally occurring radionuclides of ^{238}U, ^{232}Th, and ^{40}K. Whereas, the internal exposure is predominantly caused by naturally occurring radionuclides ^{238}U and its decay products, particularly ^{226}Ra and its associated daughter products as well as ^{232}Th and its associated daughter products (de Oliveira et al., 2001).

According to the Department of Mines and Petroleum, 2010 guideline, radionuclides from mining activities and processing sites could reach surrounding environment and ultimately, humans through aquatic release, and/or atmospheric release (DMP, 2010). Humans can be exposed to harmful substances through two primary pathways: internal exposure, which occurs via inhalation and ingestion, and exterior exposure. It is necessary to evaluate the extent of gamma radiation exposure from external sources in nearly all situations. Additionally, it may be relevant to consider the possibility of exposure through surface contamination. An exhaustive evaluation of potential internal exposure should be conducted as-needed basis, taking into consideration the routes of exposure. In addition, an accurate environmental impact assessment and remediation option evaluation needs to be estimated for naturally occurring radioactive material (NORM) contaminated sites for decommissioning and remediation purposes.

Most countries have either mining, oil, fertilizer and or related industries that generate directly or indirectly vast amount of waste with elevated levels of naturally occurring radionuclides, chemical or both. Most of these sites are either legacy or exiting operational sites with or without regulatory oversight. Many of these sites experience issues associated with soil pollution, whether radioactive, chemical, or a combination of both, typically including extensive areas of contamination. An accurate assessment of radionuclide contamination and radiological consequences is essential for impact evaluation and remediation strategy analysis. There exists a vast data of campaigns of assessing NORMs or NORM contaminated sites using diverse measuring techniques (direct or indirect, destructive, or non-destructive, contact, or non-contact) in mostly air, surface soils, and water (surface or underground water) and food. The assessment of the NORM contaminants and their radiological impact will go a long way to inform an effective radiological and environmental program for the contaminated sites.

1.2. Justification of the Research

The population is externally exposed to gamma radiation from natural radioactivity in rocks, soils, and building materials and internally through the use of drinking water, eating foodstuff, breathing air that containing natural radioactivity, mainly from ^{226}Ra, ^{232}Th, and ^{40}K and their decay products.

Mining activities, essential for economic development, significantly alter the environmental landscape and contribute to the dispersion of NORMs. These materials, which include radionuclides such as ^{238}U, ^{232}Th, and ^{40}K, are integral components of the Earth's crust. They are often released into the environment during mining and mineral processing, leading to elevated concentrations in air, soil, water, and food. The enhanced levels of these radionuclides, referred to as technologically enhanced naturally occurring radioactive materials (TENORM), presents possible radiological hazards to the ecosystems and human health (Faanu et al., 2016a, 2016b, 2024).

In Ghana, mining constitutes a major economic activity. Gold constitutes the principal mineral resource in Ghana, alongside bauxite, manganese, petroleum, natural gas, salt, silver, and diamonds; it accounts for over 95% of the nation's mineral exports. Extensive gold mining activities are concentrated in regions including the Central, Western, Eastern, and Ashanti Regions, as

illustrated in Figure 1.1 (Cobbinah and Amoako, 2018; Kazapoe et al., 2023). In 2025, Ghana's gold production was approximately 6 million ounces, and export revenues reached roughly $20 billion (GOLDBOD, 2026), contributing 6% to 8% of the nation's GDP (Sasu, 2025), thereby underscoring the sector's essential contribution to macroeconomic stability (IMF, 2025).

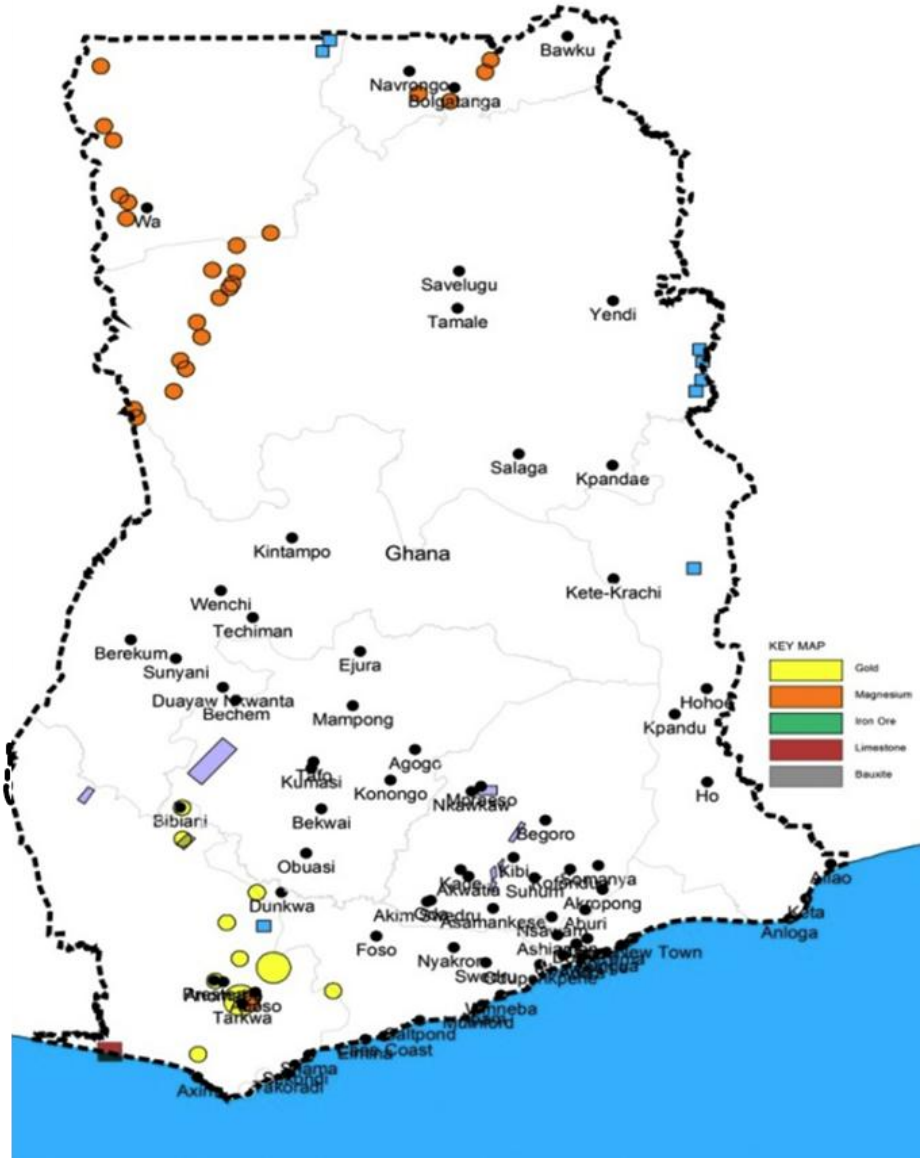

Figure 1.1. Mining areas in Ghana (Cobbinah and Amoako, 2018).

However, these mining activities have been linked to environmental contamination and the dispersion of radionuclides. Studies conducted in mining areas like Ayanfuri, Dunkwa-on-Offin, and the lower Pra River Basin reveal increased concentrations of ^{238}U, ^{232}Th, and ^{40}K in

environmental media. For example, baseline studies in the River Pra Basin identified average activity concentrations in soil of 25.51 Bq/kg for ^{238}U, 28.04 Bq/kg for ^{232}Th, and 238.98 Bq/kg for ^{40}K (Adukpo et al., 2015). In sediment, the activity concentrations were relatively lower, with 16.02 Bq/kg for ^{238}U, 20.31 Bq/kg for ^{232}Th, and 27.39 Bq/kg for ^{40}K. These concentrations often depend on local geological formations, mining processes, and waste management practices (Adukpo et al., 2015; Faanu et al., 2024; Kansaana et al., 2024).

With the ongoing increase in artisanal mining activities which are largely unregulated, there is an increasing likelihood of elevated levels of these radionuclides in soils and water bodies in these mining areas and surrounding communities. Surface water bodies are largely affected by these mining activities as shown in Figure 1.2; not only elevating the natural radionuclide contents in these waters (Adukpo et al., 2015; Akuo-ko et al., 2024; Duncan, 2020; Faanu et al., at 2016a, 2016b, 2024) but also affecting the physical properties such as the total dissolved solids (TDS), turbidity, conductivity, potential of hydrogen (pH), the organic life (plants and fishes) and introduction of other chemicals and heavy metals in the waters (Duncan, 2020; Faanu et al., 2016a, 2016b; Hogarh et al., 2016; Kazapoe et al., 2023; Kusimi and Kusim, 2012)

Figure 1.2. Devastating effects of illegal or unregulated artisanal (surface or open pit) mining on water bodies (GBC, 2024; Srem, 2017).

Also, the extensive environmental degradation due to illegal mining in Ghana coupled with the elevated levels of radium and thorium in surface waters which serves as irrigation sources farms, rais concerns about their accumulation in food crops. The increased reliance on chemical fertilizers, which often contain trace radionuclides such as ^{238}U, ^{226}Ra, ^{232}Th, and their decay products such as ^{210}Pb, ^{210}Po, and ^{222}Rn, and ^{40}K due to their phosphate content, further exacerbates the problem (Alsaffar et al., 2016; Najam et al., 2022). Studies have shown that radionuclides accumulate in various plant components including rice, depending on environmental and factors such as soil pH, irrigation practices, and fertilizer types (Asaduzzaman et al., 2015; Pulhani et al., 2005; Shanthi et al., 2012). Rice is the second most widely consumed staple food in Ghana with a consumption rate of 51 kg per person per year. Therefore, the potential uptake of these naturally occurring radionuclides from soils and irrigation water presents a potential radiological food safety concern. Especially as the impacted surface waters in these mining communities are the primary irrigation sources for the rice farms. Accumulated radionuclides may infiltrate the human body via ingestion and redistribute to organs, potentially causing health effects (Akhter et al., 2007; Nahar et al., 2018).

1.3. Research Problem

Mining operations present a possible danger of exposure to NORM in numerous African nations, including Ghana (UNSCEAR, 2000). This risk stems from the absence of thorough laws governing NORMs in active mining sites, despite the existence of numerous operational mines of varying scales (UNSCEAR, 2000).

Natural radionuclides contribute to both external gamma radiation and internal exposures, primarily through ingestion of contaminated water and food. Internal exposure is particularly concerning for radionuclides such as radium-226 (^{226}Ra) and radium-228 (^{228}Ra), decay products of ^{238}U and ^{232}Th respectively, and polonium isotopes, which are known for their high radiotoxicity. Studies have shown that water sources in mining areas often exceed the recommended World Health Organisation (WHO) and the Ghana Standards Authority (GSA) radiological screening safety limits of 0.5 Bq/L and 0.1 Bq/L for gross-alpha respectively and 1.0 Bq/L for gross-beta in the case of both the WHO and GSA (Faanu et al., 2016a, 2016b; WHO, 2017). For instance, the average activity concentrations in water samples from the lower Pra Basin were 2.51 Bq/L for

^{226}Ra, 1.71 Bq/L for ^{228}Ra, and 41.43 Bq/L for ^{40}K (Adukpo et al., 2015). These values, though within international limits in most cases, highlight the need for regular monitoring and assessment of radiological risks.

Globally, the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA) recommend a public dose limit of 1 millisievert (mSv) per year from all sources of radiation (IAEA, 2014a; ICRP, 2007). In Ghanaian mining areas, estimated annual effective doses from internal exposure and external pathways generally fall below this threshold. For example, the total annual effective dose from gamma radiation and ingestion of water in certain mining zones was found to range from 0.35 to 3.91 μSv/year, with an average of 1.82 μSv/year (Adukpo et al., 2015; Faanu et al., 2024). However, localized areas with intense unregulated mining activities or poor waste management practices may exceed safe levels, requiring intervention (Faanu et al., 2024).

The levels of natural radionuclide radiation can vary depending on the location, but in general, locations with elevated concentrations of uranium and thorium in the surface tend to have higher dose levels. Hence some trace amount of natural radioactivity can be found in all rocks and soils, and ingestion or inhalation of these substances is possible if they are disturbed (during mining activities). Enhanced radionuclide dispersion in mining environments is influenced by several factors, including soil erosion, water runoff, and improper disposal of mining waste. The radiological risks associated with these activities are not confined to the immediate mining sites but extend to surrounding communities. Studies conducted in Obuasi and Tarkwa, two major mining towns in Ghana, highlighted the importance of assessing the radiological hazard indices absorbed dose rates and radium equivalent activity. The average activity concentrations in these areas were 28.7 Bq/kg for ^{226}Ra, 25.4 Bq/kg for ^{232}Th, and 581.8 Bq/kg for ^{40}K in Obuasi, and 34.5 Bq/kg for ^{226}Ra, 20.7 Bq/kg for ^{232}Th, and 682.4 Bq/kg for ^{40}K in Tarkwa (Faanu et al., 2024). Such findings underscore the necessity of evaluating the suitability of soils as building materials (Beretka and Mathew, 1985) and ensuring the safety of water resources in mining regions and farms that uses water resources within the mining communities.

Illegal mining in Ghana has also degraded land and increased radium and thorium levels in irrigation waters, raising concerns about food contamination especially in rice cultivated in some affected areas as rice (Ghana's second most consumed food) has the natural tendency to accumulate

natural radionuclides through root uptake from soil and water (IAEA, 2006, 2014b; Pulhani et al., 2015; Shanthi et al., 2012). Radionuclide accumulation in rice varies with soil pH, irrigation, and fertilizer use, and ingestion allows redistribution in the human body, potentially causing health effects (Akhter et al., 2007; Asaduzzaman et al., 2015; Jia et al., 2014; Nahar et al., 2018; Pulhani et al., 2005; Shanthi et al., 2012)

Despite the growing body of research on radionuclide dispersion in mining areas, gaps remain in the understanding of long-term radiological impacts and the cumulative effects of mining activities on environmental health. Comprehensive radiological surveys and the establishment of baseline data are critical for effective monitoring and regulation. Furthermore, integrating radiological assessments into mining policies and waste management practices will enhance environmental sustainability and public safety (Adukpo et al., 2015; Faanu et al., 2024; Kazapoe et al., 2023).

1.4. Aims and objectives

The general aim of the study is to provide an overview of enhanced radionuclide dispersion in some selected mining communities in Ghana, focusing on the environmental and radiological implications to the public.

The specific objectives of the study are:

1. To estimate the radioactivity concentrations of
    a. ^{238}U, ^{232}Th, and ^{40}K in soils within some selected mining communities
    b. ^{238}U, ^{232}Th, and ^{40}K in leftover heap pads/soils/tailing
    c. ^{226}Ra, ^{228}Th, and ^{40}K in surface water resources in the selected mining communities.
2. To determine the extent of radionuclide contamination in Ghanaian rice farming systems due to water polluted by illegal mining and assess the related radiological health risk by.
    a. quantifying the radioactivity concentration of ^{226}Ra, ^{232}Th, and ^{40}K rice from a rice community farm affected by the mining activity.
    b. assessing radionuclide transfer factors from water to rice and soil to rice,
3. Ascertain the suitability of
    a. heap pads/soils/tailing for incorporation into construction and building materials.

b. Surface water and ground water resource as drinking and irrigation water.

4. To assess the radiological risk concerning
    a. Radium equivalent, absorbed gamma dose rate, external and internal hazard indices.
    b. Internal or committed effective doses.
    c. Associated Excess Lifetime cancer risk.

1.5. Scope and Limitation of Research

The exposure of these natural radionuclides especially in their elevated levels present some radiological health risk to the public and health the associated dose assessments were estimated in respect of radiation protection. It examines of possible mitigation measures for NORM. Hence, the study sought to assess the natural radioactivity concentrations in soil, water, and rice farms which are affected by mining activities in some selected mining communities in Ghana using gamma spectrometry analysis and gross alpha and gross beta screening methods. The corresponding radiological risk linked to the natural radioactivity levels and some recommendations were reported and made, respectively.

Samples were mostly taken from mining communities especially those affected by unregulated or illegal mining activities. These areas presented a lot of challenges and limitations such as personal security and accessibility during samples process because of their unregulated and illegal nature of the mining activity. This affected the selection of the sampling sites, the number or volume of samples collected.

Nonetheless, the reported results would serve as a base line value for these areas as well as inform stakeholder (miners, farmers, regulators and government) on the right decisions to make to ensure the proper regulation of mining activities within these communities to avert the possible harm to the environment and the public.

LITERATURE REVIEW

2.1. Naturally Occurring Radioactivity

Naturally occurring radioactivity, also known as natural background radiation, originates from the disintegration of naturally occurring radionuclides through decay processes from an unstable to a stable state, during which alpha and beta particles are emitted, sometimes accompanied by gamma radiation. Gamma radiation itself is not considered a mode of radioactive decay, but rather a mechanism by which radionuclides release excess energy. These natural radionuclides, which have always existed, are found in every environmental constituent: air, water, soil, food (both plant and animal-based), and humans. Natural radioactivity emanates from cosmic sources, called cosmogenic radionuclides, alongside radioactive elements in the Earth's crust, called terrestrial radionuclides (IAEA, 2003; UNSCEAR, 2000).

2.1.1. Cosmogenic Radiations and Radionuclides

The earth is continually bombarded by charged particles from outer space. These particles are known as cosmic radiation. Cosmic radiation is known to be the oldest naturally occurring source of radiation, originating at the beginning of the universe around 13–14 billion years ago (Cember, 2009). Based on their source and the Van Allen radiation belt, they are either galactic cosmic rays (GCRs) or solar cosmic rays (SCRs) (Spurny, 2001). Galactic cosmic rays originate outside the solar system and are composed of particles associated with solar flares that are distributed throughout the Milky Way galaxy. They are mainly composed of protons (~85%) but also contain helium nuclei (~12%), electrons (~2%), and other nuclei (~1%). They can reach energies of up to 10^{20} eV (NCRP, 1989). Solar cosmic rays (SCR), on the other hand, originate from the Sun and are almost entirely composed of protons (99%) with energy level much lower, rarely reaching 100 MeV (Spurny, 2001).

The intensity of cosmic radiation increases with altitude due to the Earth's magnetic field, high velocity charged particles are deflected as they traverse the magnetic force field (Shahbazi-Gahrouei, 2003). Cosmic rays entering the atmosphere interact with the atoms and molecules present and produce cosmogenic radionuclides, such as carbon-14 (^{14}C), tritium (^{3}H), and beryllium-7 (^{7}Be), through nuclear reactions (UNSCEAR, 2008). These radionuclides are involved

in processes on earth and can be incorporated into living organisms, including humans. However, most of these cosmogenic radionuclides (e.g. ^{14}C and ^{3}H) hold minimal or negligible significance within the realm of health physics owing to their relative infrequency and inconsequential impact on the dose from naturally occurring radioactivity. However, cosmic radiation is important in research and in interpreting health physics measurements concerning naturally occurring isotopes, especially given that the worldwide steady-state inventories of ^{3}H and ^{14}C are estimated to be 1.26×10^{18} Bq and 1.15×10^{19} Bq, respectively (Cember, 2009).

2.1.2. Terrestrial Radionuclide

Terrestrial radionuclides are believed to have existed since the creation of the Earth and are the sources of terrestrial radiation. They are typically long-lived with half-lives often amounting to millions of years. Terrestrial radionuclides generally comprise radionuclides associated with the uranium-238 (^{238}U) and thorium-232 (^{232}Th) decay chains, as well as potassium-40 (^{40}K). Three natural decay chains exist: the uranium chain, the thorium chain, and the actinium chain. In nature, the radionuclides within these three series exist in a condition of secular equilibrium, when the activity of all radionuclides in each series is almost equivalent. These three-decay series have three distinctive characteristics in common. Firstly, all three series start with a very long-lived parent radionuclide. Secondly, they all end with a stable isotope of lead. Thirdly, they all have a gaseous isotope of radon in the middle of the decay chain (Cember, 2009; IAEA, 2003; UNSCEAR, 2000).

These primordial radionuclides of terrestrial origin are the sources of natural radioactivity in the environment, and they are present in trace but significant quantities at all levels of ground formation. It is widely accepted that levels of natural radioactivity are not normalised across the globe. The distribution of radionuclides in the geosphere is contingent upon the geological medium from which they derive and the mechanisms that concentrate them in particular locales (IAEA, 2003). Just as the level of radioactivity varies regionally, so too does natural radiation exposure, as the composition of soil and rock changes.

Natural radioactivity in the environment results in human irradiation through decay processes. Over 80% of the total average exposure (2.4 mSv per year) occurs through external and internal exposure pathways (UNSCEAR, 2000). External irradiation is mainly due to gamma radiation from ground formations such as soil, resulting from decay chain processes involving ^{238}U,

^{232}Th and ^{40}K. Internal irradiation, meanwhile, is mainly due to the alpha and beta decay chain processes of inhaled or ingested natural radionuclides such as ^{226}Ra, ^{228}Ra, ^{222}Rn, ^{210}Pb, and ^{210}Po. Alpha emitters are among the most significant natural radionuclides concerning hypothetical internal radiation exposure.

Uranium is an actinide element present in the Earth's crust at an average concentration of 3 ppm (Ebaid, 2010). However, 99.3% of all naturally occurring uranium is ^{238}U, which exists in higher concentrations than average, ranging from 7 to 125 ppm, in phosphate-rich soils, as uranium and phosphorous form extremely stable compounds in soils (Cember, 2009; UNSCEAR, 2000). Most natural radionuclides originate from ^{238}U. It undergoes the 4n+2 decay chain (see Table 2.1), also known as the uranium-radium decay series and is a purely alpha-particle emitter. All decay products are transiently present in any natural uranium-containing sample. The decay chain terminates with lead-206 (^{206}Pb). ^{238}U has an affinity for electron donors (e.g. oxygen) and therefore accumulates in lung tissue and bone marrow, which can lead to blood cancer. ^{235}U, on the other hand, constitutes around 0.7% of naturally occurring uranium (Cember, 2009). Like ^{238}U, it is present at elevated levels in phosphate-rich soils and rocks. ^{235}U is also a fissionable radionuclide that can be used in a reactor if it is enriched to the required level. It is notable for its 4n+3 decay chain, which is independent of the uranium-radium decay chain: it starts with ^{235}U and ends with ^{207}Pb.

Table 2.1. Uranium decay chain

Nuclide	Decay mode	Half-life	Energy release (MeV)	Decay product
^{238}U	α	$4.468 \cdot 10^9 a$	4.270	^{234}Th
^{234}Th	β^-	24.10 d	0.273	^{234m}Pa
^{234m}Pa	β^- 99.84%	1.16 min	2.271	^{234}U-
	IT 0.16%		0.074	^{234}Pa
^{234}Pa	β^-	6.70 h	2.197	^{234}U
^{234}U	α	245500 a	4.859	^{230}Th

^{230}Th	α	75380 a	4.770	^{226}Ra
^{226}Ra	α	1602 a	4.871	^{222}Rn
^{222}Rn	α	3.8235 d	5.590	^{218}Po
^{218}Po	α 99.98%	3.10 min	6.115	^{214}Pb
	β^- 0.02%		0.265	^{218}At
^{218}At	α 99.90%	1.5 s	6.874	^{214}Bi
	β^- 0.10%		2.883	^{218}Rn
^{218}Rn	α	35 ms	7.263	^{214}Po
^{214}Pb*	β^-	26.8 min	1.024	^{214}Bi
^{214}Bi*	β^- 99.98%	19.9 min	3.272	^{214}Po
	α 0.02%		5.617	^{210}TI
^{214}Po	α	0.1643 ms	7.883	^{210}Pb
^{210}TI*	β^-	1.30 min	5.484	^{210}Pb
^{210}Pb	β^-	22.3 a	0.064	^{210}Bi
^{210}Bi	β^- 99.99987%	5.013 d	1.426	^{210}Po
	α 0.00013%		5.982	^{206}TI
^{210}Po	α	138.376 d	5.407	^{206}Pb
^{206}TI	β^-	4.199 min	1.533	^{206}Pb
^{206}Pb	-	stable	-	-

* Isotope is a significant gamma emitter with isomeric transition (IT) decay.

Source: ANL, 2005a; Cember, 2009; UNSCEAR, 2000

Thorium is another actinide element that is almost four times as prevalent than uranium (Cember, 2009; UNSCEAR 2000). Though it first appears in the ^{238}U decay scheme as ^{234}Th, it has

a naturally occurring radioisotope, ^{232}Th, which serves as the parent radionuclide for its own decay chain. This decay chain is known as the 4n series, or the thorium series (see Table 2.2). All members of the decay series are present, at least temporarily, in any natural sample containing thorium. The series ends with lead-208 (^{208}Pb). ^{232}Th, which is also an alpha particle emitter, accumulates in the lining of the bones, potentially leading to bone cancer (Cember, 2009; UNSCEAR, 2000).

Table 2.2. Thorium decay chain

Nuclide	Decay mode	Half-life	Energy release (MeV)	Decay product
^{232}Th	α	$1.405 \cdot 10^{10} a$	4.081	^{228}Ra
^{228}Ra	β^-	5.75 a	0.046	^{228}Ac
^{228}Ac*	β^-	6.25 h	2.124	^{228}Th
^{228}Th	α	1.9116 a	5.520	^{224}Ra
^{224}Ra	α	3.6319 d	5.789	^{220}Rn
^{220}Rn	α	55.6 s	6.404	^{216}Po
^{216}Po-	α	0.145 s	6.906	^{212}Pb
^{212}Pb*	β^-	10.64 h	0.570	^{212}Bi
^{212}Bi	β^- 64.06%	60.55 min	2.252	^{212}Po
	α 35.94%		6.208	^{208}TI
^{212}Po	α	299 ns	8.955	^{208}Pb
^{208}TI*	β^-	3.053 min	4.999	^{208}Pb
^{208}Pb	-	stable	-	-

* Isotope is a significant gamma emitter.

Source: ANL, 2005a; Cember, 2009; UNSCEAR, 2000

^{40}K is an alkali metal isotope widely found in the environment. It is found in crustal rock at an average concentration of about 27 g/kg. It is also found in plants and animals, including human beings, at an isotopic abundance of 0.0119% (Cember, 2009). It is the most prevalent naturally occurring radioactive substance found in soil and is used as a tracer of the stable potassium, an essential plant nutrient (Desideri et al., 2009, 2010, 2011). ^{40}K enters plant roots via ion channels or specific transporters. Once ingested, it is almost completely absorbed and quickly transferred into the bloodstream. It has a physical half-life of 1.2 billion years (see Table 2.3) and a biological half-life of approximately 30 days.

Table 2.3. Potassium-40 decay chain

Nuclide	Decay mode	Half-life	Energy release (MeV)	Decay product
^{40}K	β^- 89.28%	$1.248 \cdot 10^9 a$	1.330	^{40}Ca
	EC 10.72%		1.460	^{40}Ar
	β^+ 0.001%			^{40}Ar

Source: ANL, 2005b; Cember, 2009; UNSCEAR, 2000

The decay of ^{40}K is unique in that it is one of only three isotopes capable of undergoing all three types of beta decay. However, ^{40}K is deemed to lack radiological importance, as potassium is a vital metabolic element whose concentrations in the body remain in balance and hence do not fluctuate markedly with dietary potassium consumption. Also, the body's control systems for blood pressure and volume depend on potassium concentration, and abnormalities in this control present a general propensity for hypertension and eventual cancer development, with a lifetime cancer mortality risk of 0.814 Bq^{-1} for intake (Tettey-Larbi et al., 2013a; 2015).

2.2. Radiation exposure pathway

The act or condition of being subject to irradiation is termed radiation exposure. Although the IAEA and the ICRP categorise exposure to radiation in accordance with the following exposure groups: occupational, public, and medical, they are largely categorised as external and internal exposures (IAEA, 1996, 2014a, 2014b; ICRP, 2007). Humans are exposed to radiation daily, either from naturally occurring sources or man-made sources. Natural sources account for around 80%

of human radiation exposure, with the remaining 20% coming from man-made sources. Radon is the main source of natural radiation exposure for humans (UNSCEAR, 2000). Figure 2.1 shows the worldwide average radiation exposure sources with an average annual exposure of 2.4 mSv in typical ranges of 1 – 10 mSv as presented in Table 2.4.

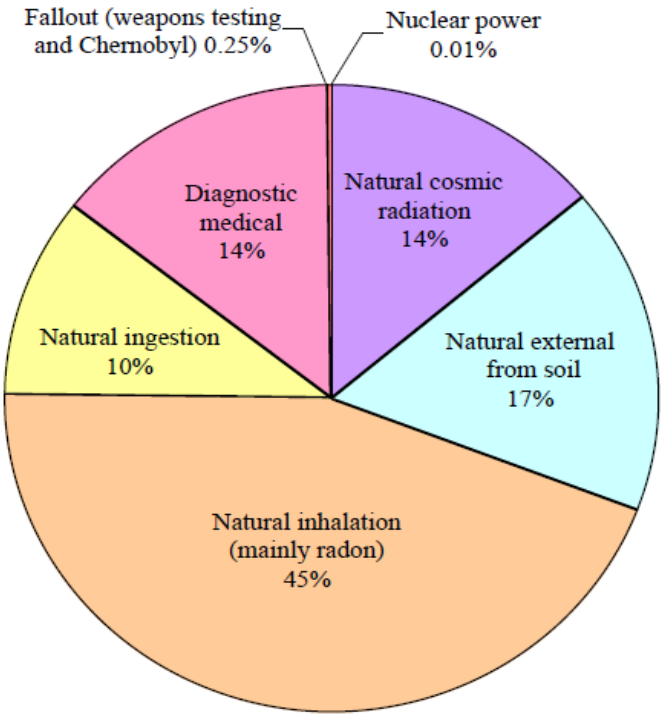

Figure 2.1. Worldwide average exposure to radiation sources (Russ et. al., 2006; UNSCEAR, 2000)

Table 2.4. Global mean radiation exposure dose from natural sources

Sources	Global annual effective dose (mSv)	Range (mSv)
External exposure		
Cosmic rays	0.4	0.3-1.0 [a]
Terrestrial gamma rays	0.5	0.3-0.6 [b]
Internal exposure		
Inhalation (mainly radon)	1.2	0.2-10 [c]
Ingestion	0.3	0.2-0.8 [d]
Total	**2.4**	**1-10**

[a] Variation from sea level to elevated terrain; [b] contingent upon the radioactive composition of soil and construction materials; [c] influenced by indoor accumulation of radon gas; [d] reliant on the radionuclide composition of foods and potable water.

Source: UNSCEAR, 2000

The exposure pathway is the route through which a radioactive material can enter the body or be exposed externally to it. There are many ways in which one can be exposed to radiation externally or internally. These include external gamma and beta irradiation, inhalation, ingestion, absorption through the skin and entry through cuts and wounds (Cember, 2009). The exposure pathway plays a key role in exposure assessment, helping to estimate the accumulated lifetime dose due to exposure to radionuclides. Radioactivity can also be ingested from food that is eaten and water that is drunk. This study considers both exposure pathways of some terrestrial natural radionuclides as well as the relative corresponding dose from those exposures as shown and highlighted in Figure 2.2.

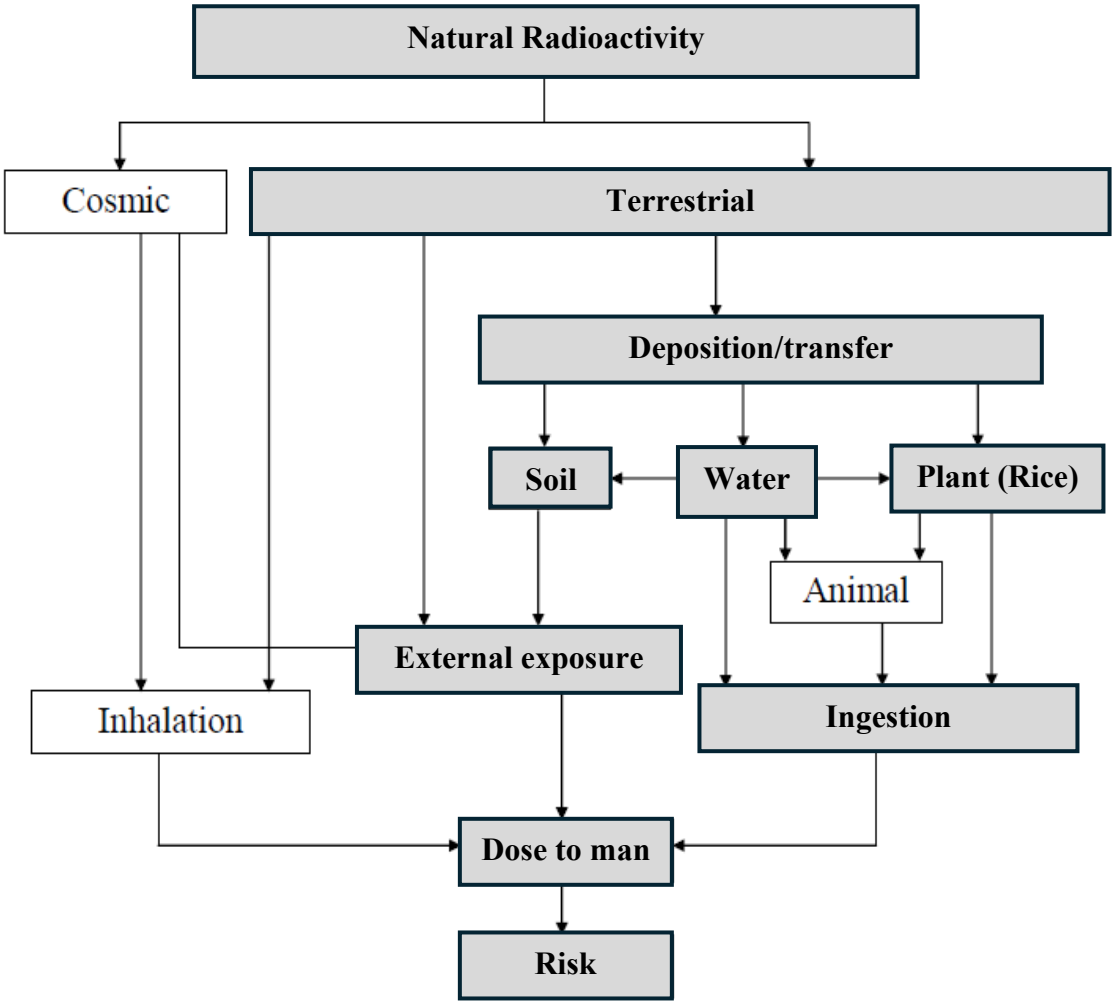

Figure 2.2. Schematic diagram of Exposure pathway due to natural radionuclides (UNSCEAR, 2000)

2.2.1. External exposure

External exposure occurs when radiation originates from sources outside the body. It may be unintentional, such as when airborne radioactive materials (e.g. dust, liquid, or aerosol) are deposited on the skin or clothing, or intentional, such as during medical diagnosis or therapy (Cember, 2009; WHO, 2011). Such exposures primarily arise from gamma radiation due to radionuclide decay outside the human body and/or secondary exposure of the skin to beta radiation (UNSCEAR, 2006, 2008). Exposure to terrestrial natural radionuclides arises from direct deposition on the skin and irradiation from such radionuclides in the soil (see Table 2.5). The external exposure pathway is of particular significance in the event of unintentional emissions of radionuclides into the atmosphere, as shown by the Chernobyl and Fukushima incident.

Table 2.5. External exposure rates derived from different concentrations of terrestrial radionuclides in soil.

Radionuclide	Activity in Soil (Bq/ kg)		Dose coefficient (nGy/h/Bq.kg)	Absorbed dose rate (nGy/h)	
	Mean value	Population-weighted mean value		Mean values	Population-weighted value
^{40}K	400	420	0.0417	17	18
^{238}U	35	33	0.462	16	15
^{232}Th	30	45	0.604	18	27
Total				**51**	**60**

Source: UNSCEAR, 2000

2.2.2. Internal exposure

These radionuclides enter the body via the food chain, the water we drink, and the air we breathe. They can also enter the body through cuts and wounds. Internal exposure from the inhalation and ingestion of natural terrestrial radionuclides (Table 2.4). Radionuclides enter plants through at least two pathways: direct deposition from the atmosphere onto the plants and re-suspended soil particles, and uptake from the soil by the roots. However, the intake of radionuclides

by humans can occur either directly by consuming the plants, or indirectly by consuming animal products where these animals have fed on such plants. The amount of uranium and thorium series radionuclides that people eat each year is between 4% and about 96% as shown in Figure 2.3. However, natural background radiation causes a wide variation in individual doses. This means that 25% of a large population have an annual effective dose of less than 1 mSv, while 10% have a dose of more than 3 mSv to 10 mSv in some typical circumstances. This results in a total of 65% with doses between 1 mSv and 3 mSv, which is not good enough (UNSCEAR, 2000).

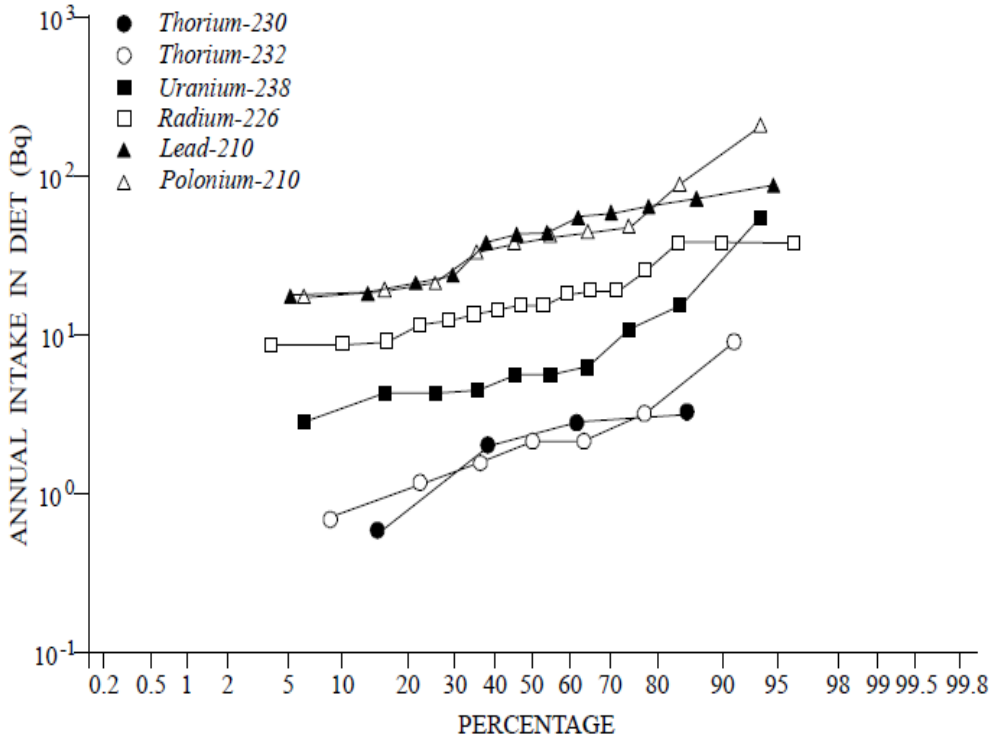

Figure 2.3. Distribution of annual intakes of natural radionuclides in diet (UNSCEAR, 2000)

All aspects of releases into the environment, whether deliberate or accidental, are subject to consideration of internal exposure. The primary objective of internal exposure assessment is to ensure the safety of individuals by preventing or reducing the intake of radionuclides, with a particular focus on naturally occurring radionuclides. Doses from the ingestion of natural radionuclides generally originate from food or plant consumption and drinking water. Therefore, it is essential that studies are conducted in all environmental fields to help reduce the annual effective dose for a large population as much as is reasonably achievable.

2.3. Radioactivity levels in soil

The soil which makes up the earth's surface is made up of unconsolidated mineral and organic matter, which develops slowly from various residual materials from the underlying parent rock crust and are modified by time, climate, macro and microorganisms, vegetation, and topography (El-Aydarous, 2007). Soils consist of organic and inorganic compounds, as well as radionuclides, which are mostly naturally occurring, terrestrial-origin radionuclides. Natural radionuclides are present in soil in trace quantities. The levels in soil depend on the type of rock from which they originate. Levels rise from sedimentary rocks to igneous rocks; however, some shales, phosphate-fortified rocks, and soils have relatively elevated levels of natural radionuclides (IAEA, 2003, 2014b). The levels are influenced by site characteristics, the soil-to-water ratio, rainfall rate and quantity, soil drainage, biochemical processes, and soil organic matter content (Abu-Khadra and Eissa, 2008). Although phosphorus and potassium are essential elements for enriching soil and optimising plant growth, soils with a high phosphate content also contain a high concentration of natural radionuclides. The concentrations of ^{232}Th and ^{40}K in phosphate-enriched soils remain virtually constant, whereas the concentration of ^{238}U in normal soils is high, at an activity concentration of about 1500 Bq/kg (Harb et al., 2008). Generally, ^{40}K has a higher activity concentration in soils than the other naturally occurring radionuclides (see Table 2.6).

Table 2.6. Natural radionuclide concentration in soil

Radionuclides	Activity in soil (Bq/kg)	
	Mean value	**Population-weighted mean value**
^{40}K	400	420
^{238}U	35	33
^{226}Ra	35	32
^{232}Th	30	45

Source: UNSCEAR, 2000

The levels of natural exposure from soil vary around the world, usually by a factor of 3, similarly, the distributions of natural radionuclides in soils are not uniform and their levels differ

from one geological region to another. However, standard levels of natural radiation exposure surpass the average amounts by factors of 10 and occasionally even 100 (UNSCEAR, 2000). Radioactivity in soil is the main source of terrestrial natural radionuclides, which enter the food chains of humans and animals through the ingestion of plants as food or medicinal sources, and through external exposure, primarily via gamma irradiation (Tettey-Larbi et al., 2013a, 2013b). However, soil radioactivity is essential not only for understanding the migration of radionuclides to humans via plants, but also for understanding changes in the natural background, which depend on factors such as the soil's geological composition and human activities (Saleh et al., 2007). Currently, the global natural radiation sources mean dose is estimated at 2.4 mSv per year (UNSCEAR, 2000).

2.4. Natural radioactivity levels in water

Water is an essential commodity of life. Globally, around 25–40% of the world's potable water is drawn from subterranean and/or surface water sources (Alomari et al., 2020; Selvi et al., 2016). People widely regard these sources as a vital water resource for human consumption and agricultural irrigation (Gordon et al., 2013).

The presence of natural radioactivity in surface waters is primarily attributable to the decay products of primordial radionuclides within the bedrock and sediment of these surface waters. However, anthropogenic activities (like mineral mining and processing, fertilisers manufacturing, burning fossil fuels, and refinery metal) raise the natural radionuclides activity concentrations in the environment. These can end up in surface water through various pathways (Pujol and Sanchez-Cabeza, 2000; Zorer and Sahan, 2011). Surface water is often polluted by surface runoff, which carries leached radionuclides from diverse sources, including mine sites and waste deposits, pedological degradation and agrarian regions (Adukpo et al., 2014; Akuo-ko et al., 2024, 2025; Faanu et al., 2024; Kansaana et al., 2024). The presence of elevated levels of naturally occurring radionuclides in surface water may be a possible health hazard, particularly when influenced by natural processes such as mining, mineral processing, weathering, deposition, and erosion (Adukpo et al., 2014; Akuo-ko et al., 2024, 2025; Turhan et al., 2013). The health risks associated with natural radionuclides in water are a global issue, prompting numerous governments to establish

suggested guideline activity concentration values for various radionuclides in drinking water (WHO, 2017).

In Ghana, surface water bodies serve as vital sources for drinking, domestic use, and irrigation, especially in rural areas. However, many of these water sources, particularly in mining communities, are polluted due to waste discharges and mining activities (Adukpo et al., 2014; Akrasi et al., 2008; Akuo-ko et al., 2025). Access to clean water remains a critical environmental issue, with rural communities facing greater challenges despite the country's abundant surface water resources (Gampson et al., 2017). Water availability fluctuates seasonally and geographically, with the southwest better supplied than the coastal and northern regions (Yidana et al., 2012). While urban areas generally have higher access to safe water, the majority of Ghanaians live in rural areas where agriculture and mining dominate, and surface water is the main source (Gordon et al., 2013). Unsustainable human activities threaten watershed management, necessitating monitoring of radionuclide sources from runoff and illegal mining. To supplement polluted surface water, about 75,000 dugouts, wells, and boreholes existed nationwide (Yidana et al., 2012).

Water quality is determined by its chemical, physical, and biological properties, which are influenced by both natural factors (e.g., soil and rock type) and human activities such as agriculture and mining. In Ghana, groundwater is generally suitable for multiple uses (Gordon et al., 2013), but radionuclide content is often overlooked. Gross alpha and beta screenings are crucial for evaluating radioactivity and health risks. The World Health Organization (WHO) recommends screening limits of 0.5 Bq/L for gross-alpha and 1.0 Bq/L for gross-beta, while the Ghana Standards Authority (GSA) stipulates stricter values of 0.1 Bq/L and 1.0 Bq/L, respectively (Faanu et al., 2016a, 2016b; WHO, 2017). Given that many surface waters in mining areas are contaminated with mine waste due to illegal mining (Bansah et al., 2018; Snapir et al., 2017), continuous radiological monitoring is necessary.

2.5. Natural radioactivity levels in plants

Naturally occurring radionuclides in soil are transferred into plants through environmental cycling and become a key pathway for radionuclides to enter the human body via the food chain (Adewumi, 2011). Plants absorb trace radionuclides during photosynthesis through root uptake of

soluble radionuclides in soil water, atmospheric deposition, and soil resuspension. Uptake via roots depends on soil concentration, while above-ground transfer depends on atmospheric deposition rates. Root uptake is considered the most significant pathway, influenced by soil properties such as pH, mineral composition, organic matter, nutrient levels, and plant physiology (IAEA, 2006).

Radionuclide concentrations in plants vary geographically and by plant type, with differences linked to food or medicinal uses (INFOSAN, 2011; Tettey-Larbi et al., 2013a, 2013b). Common food plants, including rice, contain ^{238}U, ^{232}Th, their progenies, and ^{40}K. Plant mineral content is determined by nutrient uptake potential and soil nutrient availability, with uptake rates strongly dependent on soil concentrations. The complexity of radionuclide migration in soil-plant systems has led to the use of transfer factors (TFs), which estimate radionuclide uptake by plants and support models for assessing radionuclide transport through the food chain (Chen et al., 2005).

2.5.1. Natural Radioactivity in Rice

As a global dietary staple, rice can naturally accumulate radionuclides such as ^{40}K, ^{238}U, ^{226}Ra, ^{232}Th and ^{228}Ra through the uptake of soil and water, a process that is enhanced by flooded paddy cultivation (IAEA, 2006; Pulhani et al., 2015; Shanthi et al., 2012). This makes rice an effective bioindicator of environmental radioactivity, particularly in regions with uranium-, thorium- and potassium-rich geology (IAEA, 2006; Pulhani et al., 2015; Shahbazi-Gahrouei et al., 2013; Shanthi et al., 2012). While these radionuclides are naturally occurring, chronic ingestion poses potential long-term health risks, particularly in locations with elevated background radiation due to geological factors or human activities such as mining (IAEA, 2005; UNSCEAR, 2000). Furthermore, mining waste mismanagement can redistribute radionuclides, with Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) contaminating food chains through leaching and bioaccumulation (IAEA, 2003).

In Ghana, rice is the second most widely consumed staple food after maize with a national rice consumption of 1.75 million metric tons (MMT), and it is central to food security and nutrition in the country (Dickson-Agudey et al., 2026; MoFA, 2024; Muthayya et al., 2014). Consumption has increased from 22.6 kg per person per year between 2002-2004 to 51 to 52 kg per person per year in recent years (2024-2025) with over 70% of rice imported, making local production a strategic priority (Dickson-Agudey et al., 2026; MoFA, 2024). However, concerns over

radionuclide uptake from contaminated water sources pose a risk to both consumer confidence and public health. Despite rising consumption and reliance on local production, radiological studies on Ghanaian rice are limited (MoFA, 2024; Somado et al., 2008). Farms located on granitic soils, which are naturally rich in uranium and thorium, as well as those affected by illegal mining, are at a higher risk of radionuclide redistribution (Dinh Chau et al., 2011). Flooded paddies, irrigation, fertiliser inputs, and soil pH further enhance the mobility and transfer of radionuclides to rice plants.

International studies have shown variable levels of radionuclides in rice. In Taiwan, for example, the average levels of ^{40}K and ^{226}Ra were 24.05 ± 10.21 Bq/kg and 0.62 ± 0.61 Bq/kg respectively, which is well below the public limit of 1 mSv/year (Chiang et al., 2023). In southern Thailand, the mean values of ^{226}Ra, ^{232}Th and ^{40}K were 3.01, 2.76 and 29.46 Bq/kg respectively, corresponding to an ingestion dose of 85 μSv/year (Sithong et al., 2024). This is consistent with the global estimate of 290 μSv/year provided by UNSCEAR (2000). In Iraq, however, unusually elevated levels of ^{40}K (>1500 Bq/kg) were reported, though the resulting dose remained acceptable (around 250 μSv/year) (Salman et al., 2019). Relatively low levels of ^{226}Ra (1.09 Bq/kg), ^{228}Ra (0.17 Bq/kg) and ^{40}K (4.70 Bq/kg) were found in Bangladeshi rice, with doses under 65 μSv/year (Chattopadhyay et al., 2018).

2.6. Health effects of Ionising radiation

Exposure to ionising radiation can damage living cells and tissues, potentially leading to mutations or cell death. The body's coding systems, DNA and RNA, can repair such damage, but the process is often imperfect, especially in the case of mutations, resulting in adverse health outcomes. Ionising radiation causes ionisation of atoms, which may affect molecules, cells, tissues, organs, and ultimately the entire body, producing biological effects that manifest as health impacts. These effects are random; the same dose may cause different outcomes each time, or none at all.

At the cellular level, ionising radiation interacts with atoms, causing excitation or ionisation of tissue. This produces charged water molecules and extremely reactive free radicals, including hydroxyl radicals. DNA damage may occur directly via ionisation or indirectly through free-radical interactions, leading to mutations or cell death. No adverse health consequences have been shown in persons exposed to low doses (<0.1 Sv) over extended durations, with the exclusion of

radiogenic effects (mostly cancer), which are observable in epidemiological studies at doses exceeding 0.05–0.1 Sv administered at high dose rates (HPS, 2004). Nonetheless, the linear non-threshold (LNT) hypothesis assumes that any dose, no matter how small, carries some risk, and that risk increases proportionally with dose (ICRP, 1991; 2005).

The Internation Commission for Radiation Protection (ICRP) provides dose limits to manage these risks: equivalent dose limits prevent deterministic effects by remaining below tissue thresholds, while effective dose limits reduce stochastic risk using detriment-adjusted nominal risk coefficients, based on the LNT model and a dose-rate effectiveness factor of 2. The degree of radiation-induced damage to tissues and/or organs is contingent upon the received dose. The possible harm resulting from an absorbed dosage is dependent on the radiation type (alpha, beta, gamma, or neutron) and the sensitivity of various organs and tissues. The effective dose (sievert, Sv) quantifies the potential harm of ionising radiation, including both the radiation type and the sensitivity of tissues and organs. Children and teenagers exhibit markedly greater sensitivity to radiation exposure compared to adults (IAEA, 2004; WHO, 2009). The severity of radiation damage depends on the absorbed dose, radiation type, and the sensitivity of specific tissues and organs. Health effects are broadly categorised into deterministic (non-stochastic) and stochastic effects. Deterministic effects have a threshold; severity increases with dose and include tissue reactions such as cataracts or skin changes. Stochastic effects, by contrast, are probabilistic, increase with dose, and include cancer and heritable mutations, without a threshold (Nobuyuki and Yuki, 2014).

2.6.1. Deterministic Health Effects

The severity of certain effects of radiation exposure of humans increases with increasing doses, as was discovered by scientists who collected a large number of experimental evidence involving animals over the years and used theoretical reasoning to support their findings. The effect will only occur if the threshold is reached. This effect is called the deterministic health effect, formally called non-stochastic effects, and examples of this include skin burns, hair loss, and vomiting (Fry, 2001; ICRP, 1991). The majority of these effects are caused by short-term exposure to high levels of ionising radiation. The occurrence of the effects below the threshold differs to a relatively small degree between individuals. At elevated levels (>0.5 Sv), cells might be destroyed, and the capability of irradiated tissue or an organ might be impaired. However, if the dose is high

enough (for levels >2 Sv), radiation can damage the body's tissues and organs, causing a range of acute effects. These encompass erythema, alopecia, radiation-induced dermal injuries, acute radiation syndrome, and mortality, or lead to more severe conditions that are clinically evident in affected persons shortly after exposure (IAEA, 1996; Kaul et al., 1997). Cell death and delayed cell division are signs of deterministic effects resulting from impaired tissue function. These effects are caused by exposure of cells or tissues to high levels of radiation and become more severe with higher doses and dose rates.

2.6.2. Stochastic Health Effect

Low-dose ionising radiation exposure over time can result in stochastic effects, which are health effects that occur by chance and the risk is significantly diminished on account of the increased probability of rectifying the damage. The severity of the effect is independent of the absorbed dose, but the longevity of continuous exposure to low doses. The effect is probabilistic under certain exposure conditions, which means that it is not guaranteed to happen. In other words, the likelihood of an individual experiencing an effect increases with the dose received and in the absence of a threshold, it is uncertain whether the effect will occur. These effects will not always occur, but their likelihood increases with the radiation dose. There remains, nevertheless, a risk of long-term consequences, including cancer, which may manifest years or even decades later. Stochastic effects are sub-grouped into somatic and hereditary effects. Somatic effects are the detriment an exposed individual endures throughout their lifespan, including radiation-induced cancer and sterility and cataracts, or a shortened life, as a result of modifications to their somatic cells. Twenty percent of deaths in developing countries are attributed to cancer (UNSCEAR, 2000). However, Hereditary or genetic impacts refer to radiation-induced alterations in an individual's genes and DNA. These can contribute to the birth of a defective descendant as a result of a cell's modification that transmits hereditary information (Suntharalingam et al., 2005; TAEC, 2009). It should be noted, however, that radiation-induced genetic effects have not yet been found in the human population, however they have been evidenced in other mammalian populations (AAPM, 1986; IAEA, 1996; NDT, 2011). The health effects mentioned are direct effects that affect the individual who was exposed, and they may experience the effects themselves or pass them on to their offspring in a later generation. However, there are other direct or indirect effects suffered by infants in the embryonic or foetal stage due to the sensitivity of dividing cells during certain periods

of pregnancy when the expectant mother is exposed to radiation doses, whether intentionally or accidentally, that are below or above the threshold value for pregnant women.

2.7. Methods of assessment of radionuclides in environmental media

The assessment of naturally occurring radionuclides in environmental samples involves three main types of spectrometry, namely alpha, beta and gamma-ray spectrometry, depending on the types of radionuclides and their decay modes under study. However, each method has its own merits and demerits. Gamma-ray spectrometry is the most widely used of the three. This study uses gamma ray spectrometry to analyse soil, water, rice samples as well as gross alpha and beta screening of water sampled from boreholes and dug wells within the mining communities.

2.7.1. Gamma-ray spectrometry

Gamma-ray spectrometry is a method that has been employed extensively and is considered appropriate for both qualitative and quantitative analysis (Schipper et al., 2011; Somlai et al., 2006, 2008). It is a potent, non-destructive analytical tool, used to determine gamma emitters both qualitatively and quantitatively in environmental samples, such as solid, liquid, and gaseous samples, provided that appropriate sample holders are employed. The necessity for a larger sample volume is contingent upon the geometry and measurement time employed. The geometry of the sample holder is characterised by the Marinelle geometry beaker/container. The basis for qualitative determination is that the gamma rays emitted by each isotope are discrete in energy due to the transition between excited atomic orbits and are characteristic of the emitting isotope, which can be identified from them (Abo-Elmagd et al., 2010; Justo et al., 2006; Somlai et al., 2006, 2008). The quantification of the phenomenon is based on the intensity of the incoming radiation. It is imperative to note that gamma radiation possesses a high penetrating power, a high density, and a high number of orders. Consequently, in order to maximise the number of detectable interactions in the space occupied by the detector, it is essential to employ a high number of orders for the detection of gamma radiation (Chang et al., 2008).

A number of detectors can be employed for the purposes of gamma-ray spectrometry. These detectors include gas ionisation detectors such as the ionisation chamber and the proportional counter, but not the Geiger-Müller counter. Scintillation detectors such as inorganic NaI, CsI and

BGO ($Bi_4Ge_3O_{12}$), and some organic plastic scintillators, can also be used for gamma spectrometric purposes. However, their energy resolution and lowest detectable energy may limit their use in qualitative determination. There is however a plethora of semiconductor detectors available, including Si(Li) detectors, Si(p-i-n) detectors, Si drift detectors (SDD), SiC detectors, Ge(Li) detectors, and the widely utilised GaAs, CdTe, and CdZnTe detectors employed in aerospace applications. Gamma spectrometry systems have P-type or, more commonly, N-type sodium iodide (NaI) detectors or high purity germanium (HPGe) coupled with a computerised detection and recording system. However, unlike the NaI, the HPGe cannot function at room temperature owing to its low bandgap and hence it requires cryogenical cooling with Liquid nitrogen (LN_2) coupled to heavy ancillary equipment (Carchon et al., 2007; Lintereur et al., 2008). This reduces the substantial leakage current caused by thermally produced charge carriers (Kumar et al., 2020; Pennicard et al., 2017). There are considerations of researching into electrically cooled HPGe detectors to obviate the necessity for LN_2, particularly for autonomous measuring systems (Carchon et al., 2007). Nevertheless, N-type HPGe detectors are favoured over NaI detectors due to their superior resolving power and are highly recommended for environmental safeguarding analysis of all types of environmental samples (Ebaid, 2010; Tosheva et al., 2004; Turhan et al., 2011). High purity Germanium (HPGe) detectors exhibit an exceptional resolution of around 0.2% at 662 keV (Kumar et al., 2020; Milbrath et al., 2008). Nevertheless, because to their superior energy resolution and high efficiency, they are utilised in mobile platforms with increased payload capacity, such as vans (with or without shielding) and manned aircraft, as well as in backpack systems (Kumar et al., 2020; Marques et al., 2021).

As the isotopes U, Ra and Th are established through their daughter elements, an equilibrium of ^{238}U and ^{226}Ra must be postulated (though this may not be viable owing to disparate chemical properties), a waiting period of four weeks or 30 days is mandatory to attain a secular equilibrium between ^{226}Ra and its daughter elements (Faanu et al., 2016a, 2016b; Tettey-Larbi et al., 2013a). Determination of the activity concentration of ^{238}U or ^{226}Ra is possible through the use of one or more gamma peaks of ^{214}Pb and ^{214}Bi, dependent upon the attainment of secular equilibrium. The activity concentrations of ^{232}Th and ^{228}Th are typically determined from the activity concentrations of ^{228}Ac and ^{208}Tl, using the principle of secular equilibrium. In contrast, the activity concentration of ^{40}K is determined directly from the ^{40}K gamma peak at 1460 keV.

Table 2.7 presents the gamma energies and yields of the measure decay isotopes employed in this study to ascertain the natural radionuclides of interest.

Table 2.7. Natural Radionuclides gamma emitting isotopes to me determined via their decay measured isotopes

Isotope of interest to be determined	Decay products (measured isotope)	Gamma-energy (keV)	Gamma yield
^{238}U or ^{226}Ra	^{214}Pb	295	0.1828
		351	0.3534
	^{214}Bi	609	0.4516
		1120	0.1478
^{232}Th ^{288}Th	^{208}Tl	583	0.3055
		2614	0.3585
	^{228}Ac	911	0.258
^{40}K	^{40}K	1460	0.1066

2.7.2. Gross Alpha and Gross Beta Screening/Counting

Gross alpha and beta screening are crucial for evaluating overall radioactivity in water and assessing health risks from radionuclide ingestion. Gross alpha and beta counting have been identified as a fundamental screening approach for environmental and drinking water monitoring (Montana et al., 2013; Perera, 2005; Tsroya et al., 2018). Alpha-emitting radionuclides like uranium and radium isotopes pose significant internal hazards due to their high ionization potential, while beta emitters such as ^{40}K primarily contribute to radiation exposure through ingestion and metabolic processes. Studies identify eight main alpha or beta emitters of radiological concern via ingestion from the ^{238}U decay series (^{234}U, ^{226}Ra, ^{210}Pb, ^{210}Po), the ^{232}Th decay series (^{228}Ra, ^{228}Th, ^{212}Pb), and ^{40}K (Lasheen et al., 2008; Tettey-Larbi et al., 2013b; UNSCEAR, 2000; WHO, 2017). The importance of these findings lies in the potential health risks from long-term ingestion of water with high alpha and beta activity, as chronic exposure to alpha emitters like radium and uranium is linked to bone cancer and kidney toxicity (Rowland et al., 1978). Additionally, elevated beta activity may signal contamination from anthropogenic sources such as industrial discharge or

phosphate fertilizers, which can introduce carcinogenic isotopes of U, Ra, Po, and Pb (El-Taher and Makhluf, 2010; UNSCEAR, 2000).

Gas-less automatic gross alpha and gross beta counting systems furnished with Passivated Implanted Planar Silicon (PIPS) detectors are increasingly being used for rapid, low-background screening of various samples, including air filters, smears, and wipes (Jobbagy et al., 2015; Montana et al., 2013; Tsroya et al., 2018). This approach has been shown to yield performance advantages over traditional gas-flow proportional counters. The PIPS technology is distinguished by its thin entrance windows (< ~500 Å Si equivalent), low leakage current, SiO_2 passivation, and rugged implanted junctions. This offers high energy resolution, low noise, and stability over time and temperature, which lead to reduced background tailing and better discrimination between alpha and beta radiation (Mirion, 2022). The efficiencies reported for alpha (^{241}Am) range from 30–40%, while those for beta ($^{90}Sr/^{90}Y$) are 20–40%, with minimal alpha background counts. These characteristics offer practical advantages for routine monitoring without the need for consumable gases (Mirion, 2022). In general, gas-less automatic PIPS-based counters constitute a potent solution for gross alpha/beta screening when lower detection limits, portability or more straightforward maintenance are imperative. Nevertheless, trade-offs in sample handling and calibration protocols must be acknowledged (Tsroya et al., 2018).

MATERIALS AND METHODOLOGY

3.1. Introduction

This chapter provides a summary of the study area, the sample collection, the protocol for sample preparation and the analytical technique employed for analysis of the samples collected within the study area and the measured activity and corresponding derived radiological hazards.

3.2. Study Area

The study was conducted in locations with unregulated artisanal mining activities, which are characterised by significant environmental interactions with naturally occurring radionuclides (Figure 3.1).

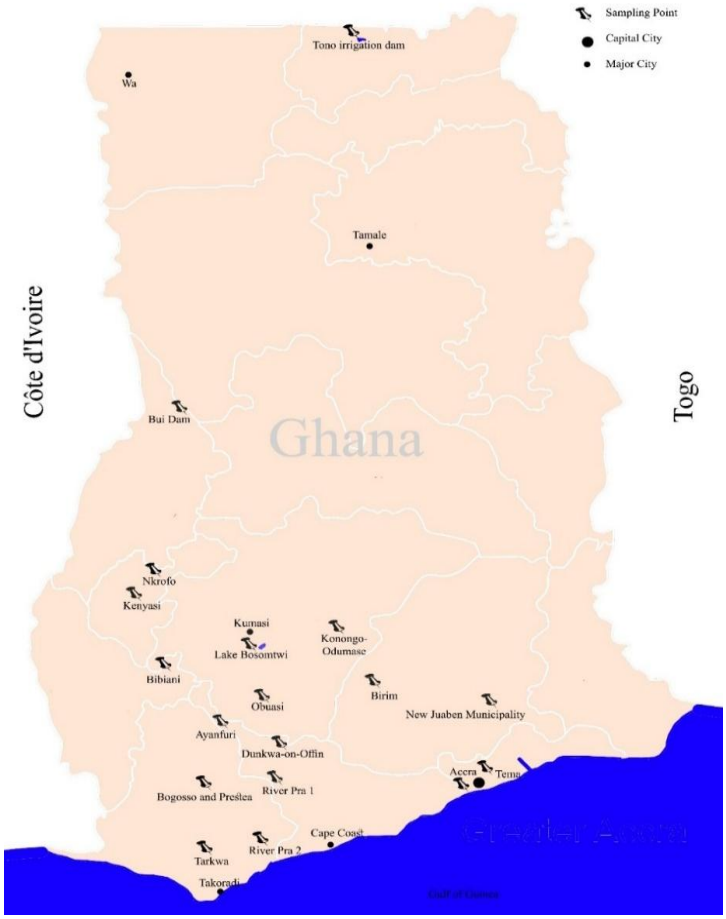

Figure 3.1. Sample's geographical locations

These locations were chosen based on their geological relevance, history of mining activities, and potential for radionuclide accumulation in environmental media and most importantly, their closeness of these mining activities to or on water bodies (rivers, streams, and open wells) as shown in Figure 3.2.

Figure 3.2. Mining activities near or on waterbodies (Agbeko, 2024; Arah, 2015; Yeboah, 2013)

Table 3.1 provides a summary of the description of the sampling area while Table 3.2 profiles the sampling in terms of the type and quantity of the sample taken.

Table 3.1. Summary description of the study areas

Location	Coordinates	Population	Remarks	References
Accra	coastline ~125 km	5,455,692	Sand mining; tourism; coastal economy.	Akuo-ko et al., 2023; Faanu et al., 2024; Ghana Statistical Service, 2021, 2022
Ayanfuri	05°28′37.8″ N, 00°52′03.5″ W	4,660	Gold mining town	Faanu et al., 2013b, 2016a; Ghana Statistical Service, 2021, 2022
Bibiani	06°27′10.6″ N, 02°18′53.85″ W	21,583	Gold mining (open pit and underground) and farming.	Faanu et al., 2014; Ghana Statistical Service, 2021, 2022
Bogoso Prestea	05°30′ N, 02°02′ W	229,301	Gold mining and farming.	Faanu et al., 2024; Ghana Statistical Service, 2021, 2022; Prestea-Huni Valley Municipal Assembly, 2024)
Bui Dam	08°16′42″ N, 02°14′09″ W	31,216	400 MW hydroelectric dam; irrigation; fishing;	Bui Power Authority, 2011; Environmental Resource Management, 2007; Faanu et al., 2024; Ghana Statistical Service, 2021, 2022

Dunkwa-on-Offin	05°58′03.3″ N, 01°47′15.3″ W	33,379	Small-scale gold mining;	Faanu et al., 2024; Ghana Statistical Service, 2021, 2022
Kenyasi	06°58′60″ N, 02°22′60″ W	15,637	Gold mining and Farming	Faanu et al., 2024; Ghana Statistical Service, 2021, 2022
Konongo-Odumasi	06°37′00″ N, 01°13′00″ W	41,238	Gold and Manganese mining	Boadi et al., 2013; Faanu et al., 2024; Ghana Statistical Service, 2021, 2022
Lake Bosomtwi	06°30′ N, 01°25′ W	67,526	Freshwater lake; fishing, irrigation, eco-tourism.	Faanu et al., 2024; Ghana Statistical Service, 2021, 2022; Lissewske, 2003; Turner et al., 1996
New Abirim	06°18′ N, 00°59′ W	11,387	gold mining and Farming.	Faanu et al., 2016b, 2024; Ghana Statistical Service, 2021, 2022; Monthel et al., 2001
New Juaben	06°13′14″ N, 00°31′84″ W	183,727	Fertile farmlands (cocoa).	Faanu et al., 2024; Ghana Statistical Service, 2021, 2022; Gyenfie et al., 2022
Nkrofo	04°57′50″ N, 02°19′20″ W	36,409	Gold mining; farming (cocoa, oil palm).	Faanu et al., 2024; Ghana Statistical Service, 2021, 2022
Obuasi	06°12′ N, 01°40′ W	115,564	Gold mining town	Faanu et al., 2013a, 2024; Ghana

				Statistical Service, 2021, 2022; Kubi Forest Mining Project, 2003
River Pra	06°33′59″ N, -0°57′23″ W	~4.2 million (basin population)	Drainage 23,188 km²; illegal mining pollution.	Adukpo et al., 2015; Duncan et al., 2023; Ghana Statistical Service, 2021, 2022
Tarkwa	05°15′ N, 02°00′ W	218,664	Gold mining belt; oil and gas NORM residues.	Ayotri et al., 2002; Faanu et al., 2013; Ghana Statistical Service, 2021, 2022; Kansaana et al., 2024; Kortatsi 2004, Kuma and Younger, 2001; Yankey et al., 2011
Tema	05°39′ N, 00°00′ (coastal)	292,773	Industrial city; harbour, oil refinery;	Darko et al., 2012; Faanu et al., 2024; Ghana Statistical Service, 2021, 2022
Tono Irrigation Dam	10°52′55.53″N, 01°09′55.31″ W	4,985	Irrigation dam; 3,600 ha; farming, fishing; domestic water supply.	Acheampong et al., 2014; Agalga et al., 2013; Ghana Statistical Service, 2021, 2022; Naabil et al., 2017

Table 3.2. Sampling profile of the study area

Study area	Type of same collected	Samples size
Accra	Beach Sand	Sand (10), water (3)
Ayanfuri	Soil and water	Soil (10), water (5)
Bibiani	Soil and water	Soil (8), water (3)
Bogosso-Prestea	Soil and water	Soil (10), water (5)
Bui Dam	Sediment and Water	Sediment (8), water (3)
Dunkwa-on-Offin	Soil and water	Soil (8), water (3)
Kenyasi	Soil and water	Soil (8), water (3)
Konongo-Odumase	Soil and water	Soil (8), water (3)
Lake Bosomtwi	Sediment and water	Sediment (8), water (3)
New Abirim	Soil and water	Soil (10), water (5)
New Juaben	Soil and water	Soil (8), water (3)
Nkrofo	Soil and water	Soil (8), water (3)
Obuasi	Soil and water	Soil (10), water (5)
River Pra	Sediment and water	Sediment (10), water (5)
Tarkwa	Soil, water, Sludges [a], and scales [b], Heap pad soil [c]	Soil (10), water (5), Sludge (5), scales (5) Pad Soil (96) [d]
Tema	Soil and water	Soil (8), water (3)
Tono irrigation dam	Sediment and water	Sediment (8), water (3)

[a] Sludge refers to the semi-solid material formed from the settling or precipitation of suspended particles during mineral processing; [b] scale is a hard mineral deposit that forms on the internal surfaces of processing pipes due to the precipitation of dissolved minerals; [c] Heap pad soil samples from leach facility under consideration to be incorporated into building and/or construction materials; [d] samples were taken at two different depths of 0-20 cm and 20-50 cm.

Locally grown rice (*Oryza sativa* and *Oryza glaberrima*) samples were also collected within the Akyemansa District, in the Eastern Region of Ghana as shown in Figure 3.3. The area is drained by tributaries of the River Birim and River Pra and is primarily agrarian, with rice cultivation being a major agricultural activity (Adukpo et al., 2015; Faanu et al., 2016a, 2016b).

These rivers are known for their prevalent illegal small-scale mining activities which have turned the river into muddy river and are suspected to elevate environmental radioactivity. Same rivers serve as irrigation source for the rice farms in the area.

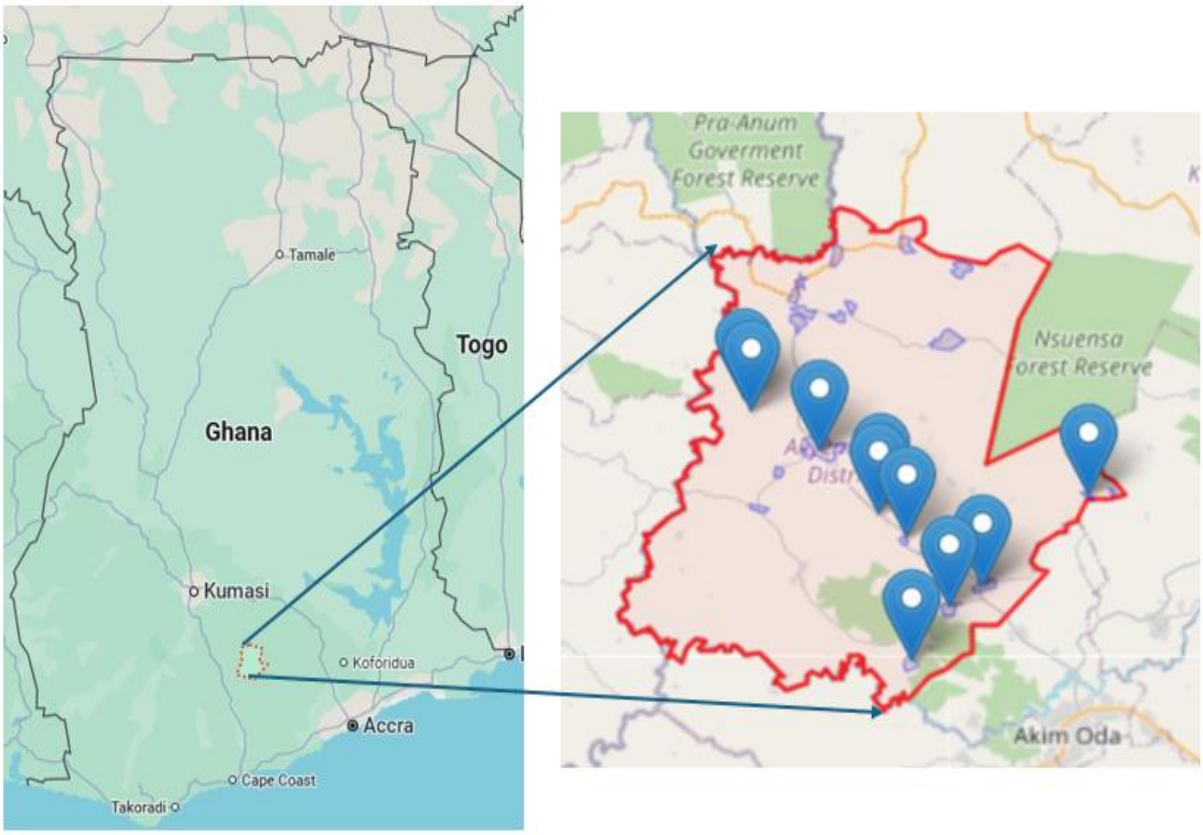

Figure 3.3. Rice sampling point of rice farms.

3.3. Sample collection and sample preparation

Soil samples were collected systematically at depths of 0–20 cm within 20x20 m^2 from the selected locations with 8–10 subsamples randomly collected to ensure representative coverage; except for the heap pad soils, where additional samples were taken at depth of 20–50 cm into ziplock plastic bags with appropriate labelling using a shovel and soil auger. The leftover heap pad soils were only sited and sampled in Tarkwa in addition to soils from the same study area. Additionally, sludges and scales samples were also collected from the Tarkwa site for analysis. As both sludge and scale are known to act as sinks for radionuclides, particularly ^{238}U, ^{226}Ra, and ^{232}Th, as a result of adsorption, co-precipitation, and chemical substitution processes.

Consequently, these materials are often considered important reservoirs of technologically enhanced naturally occurring radioactive materials (TENORM) in industrial environments (IAEA, 2003; UNSCEAR, 2008).

For the rice samples, seventy (70) samples were collected from ten (10) towns across the district, with seven (7) samples obtained per town at each town's local harvesting gathering points. into clean labelled ziplock bags and transported to the laboratory for further processing.

The soil and rice samples underwent air drying for 7 days under ambient conditions to remove moisture, followed by oven-drying at 105°C for 3 to 4 hours to ensure complete moisture elimination. The desiccated soil and rice samples were pulverised into a fine powder via a stainless-steel ball mill or mortar and pestle (especially for soil samples depending on the sample course size) and subsequently sieved through a 2 mm screen to ensure homogeneity.

For the water samples, 3–5 representative samples were taken from both surface water bodies including rivers, and ponds (including leftover pits), and groundwater samples (boreholes and hand dug wells) at different locations within the mining affected communities per community. A minimum volume of 1500 mL was collected for each sample location in acid-washed polyethylene bottles to prevent contamination and adsorption of radionuclides onto container surfaces. The surface water samples were pre-concentrated by gradual evaporation on hot plate at 80 ^{o}C to reduce the volume to 1 L and improve detection sensitivity.

To ensure stringent assurance quality of sampling procedure, the 'Recommended Practice for Investigation and Sampling Soil and Rock for Engineering Purposes', the 'Standard Method for Sampling Surface Soils for Radionuclides' and the 'Standard methods for sampling water for radionuclide' analysis were followed at each sampling location, in conjunction with an internal quality assurance manual for sample preparation (ASTNM 1983, 1986, DOE, 1998, IAEA, 2014b, 2022, 2023).

3.4. Measuring Techniques

3.4.1. Gamma Spectrometry

A high-purity germanium (HPGe) detector was employed for gamma-ray spectrometric analysis. The system included shielding to minimize background radiation and multichannel analysers for data acquisition. Calibrations for energy and efficiency were conducted utilising approved standards reference materials and standard solutions supplied by the IAEA. These calibrations spanned the energy range of 60–2000 keV to ensure accurate radionuclide identification and quantification. Activity concentrations of ^{238}U, ^{226}Ra, ^{232}Th, and ^{40}K were determined in soil, heap pad soil and rice samples, and ^{226}Ra, ^{228}Th, and ^{40}K were determined in the water samples. Gamma-ray peaks used for quantification included 609 keV (^{214}Bi) and or 351 keV (^{214}Pb) for ^{238}U or ^{226}Ra (in soil, heap pad soi, sludge, scale, water, and rice), 911 keV (^{228}Ac) and or 583 keV (^{208}Tl) for ^{232}Th (in soil, heap pad soil, sludge, scale and rice) or ^{228}Th (in water), and 1460 keV for ^{40}K in all samples (Faanu et al., 2024; IAEA, 2014a, 2014b; Kansaana et al., 2024). For the gamma spectrometry analysis, the processed samples (soil, heap pad soil, sludge, scales and water) were sealed in 1 L Marinelli beakers, weighed and stored for at least 4 weeks to achieve secular equilibrium in the determination of the radionuclides of interest ^{238}U, ^{226}Ra, ^{232}Th, ^{228}Th, ^{40}K and their progeny before counted for 80,000 seconds (Akuo-ko et al., 2024, 2025; Faanu et al., 2013a, 2013b).

3.4.2. Gross Alpha and Gross Beta Counting

For the gross alpha and beta screening of the boreholes and hand-dug wells water samples, each water sample was acidified with 1 mL of concentrated nitric acid (HNO_3) per Liter to maintain the stability of dissolved radionuclides and prevent precipitation. Water samples were evaporated to near desiccation on a hot plate within a fume hood. The residue was dissolved in 1 M HNO_3, transferred to a stainless steel planchet, and heated to remove any remaining moisture. The planchets were stored in a desiccator to prevent reabsorption of moisture prior to analysis (Faanu et al., 2016a; Tettey-Larbi et al., 2013b). The methodology provides a comprehensive framework for assessing radionuclide activity concentrations and associated radiological risks, contributing to the understanding of environmental radioactivity in mining-affected areas. Water samples were

examined via a gas-less automatic alpha-beta counting system (Canberra iMatic™) fitted with passivated implanted planar silicon (PIPS) detectors. The system was calibrated with standard alpha (^{241}Am) and beta (^{90}Sr) sources to determine detection efficiencies. Background corrections were applied to improve measurement accuracy. Gross alpha and beta activities were measured over 4 hours for each water sample to ensure statistical reliability (Tettey-Larbi et al., 2013b)

3.5. Radiological Calculations and Risk Assessment

3.5.1. Activity Concentrations

Prior to the determining of the activity concentration, the Minimum Detectable Activity (MDA) at 95% confidence level for each radionuclide was calculated using the Currie equation (Currie, 1968), which considers background count (B), gamma yield (ρ), counting time (T), detector efficiency (η), and sample mass or volume (M); expressed in the formular in equation 1:

$$MDA = \frac{2.71+4.65\sqrt{B}}{\eta.\rho.T.M} \quad (1)$$

The background spectra were measured under the same experimental conditions as the samples using an empty Marinelle container to determine the background counts within the ROI of each photopeak. Detector efficiency values were obtained from prior efficiency calibration of the gamma spectrometry system. The calculated MDA values were used to assess the minimum activity concentration of radionuclides that could be detected in the analysed samples. Activities measured below the corresponding MDA were considered not detectable under the applied measurement conditions and only concentrations above the calculated MDA were considered in further analysis.

The activity concentrations of radionuclides in the soils, heap pad soil, sludges, scales, surface water, and rice samples were estimated using the following formula in equation 2:

$$A_s = \frac{N}{\rho.T.\eta.M} \quad (2)$$

where: A_s is the activity concentration of the radionuclide of interest (in soil, heap pad soil, sludges, scales or rice, Bq/kg or in water, Bq/L); N is the net count rate (cps); ρ is the gamma yield; T is the

counting time (s); η is the detector efficiency; and M is the mass (for soil, heap pad soil, sludges, scales or rice, kg) or volume (for water, L) of the sample under investigation.

The gross alpha and gross beta activities concentration ($A_{\alpha,\beta}$) screening of the borehole were estimated from the corrected gross alpha or gross beta activity concentration activity from the detector (A_w), per Liter of the water sample used (V_w) based on equation 3 (Faanu et al., 2016a; Tettey-Larbi et al. 2013):

$$A_{\alpha,\beta} = \frac{A_w}{V_w} \quad (3)$$

3.5.2. Radiological Hazard Indices of the soil samples

Absorbed dose rates (D_γ) in air were calculated (nGy/h) as the summation of the external conversion factors (CF_{ext}) expressed in nGy/h per Bq/kg specific to activities (A_s) of ^{40}K (0.0417), ^{238}U (0.462) and ^{232}Th (0.604) in the soils using equation 4 (Shahrokhi et al., 2023)

$$D_\gamma(\text{nGy/h}) = \sum CF_{ext}(U, Th, K) \times A_s(U, Th, K) \quad (4)$$

In evaluating the radiological hazard indices to determine the safety of soils for construction and or incorporation into building materials and the risk to public health, the radium equivalent, Ra_{eq} (Equation 5), used to represent the total radioactivity from ^{226}Ra, ^{232}Th, and ^{40}K in a single index, Gamma Index, Iγ (Equation 6), the external hazard index, H_{ex} (Equation 7) and internal hazard Index, H_{in} (Equation 8) were estimated using the formulas below, where Ra was taken as being in secular equilibrium with U (Beretka and Mathew, 1985; da Silver et al., 2024; Higgy, 2000; Shahrokhi et al., 2023)

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_K \quad (5)$$

$$I_\gamma = \frac{C_{Ra}}{300} + \frac{C_{Th}}{200} + \frac{C_K}{3000} \quad (6)$$

$$H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad (7)$$

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad (8)$$

Subsequently, the outdoor annual external effective dose (E_{ex}) was calculated from the absorbed dose rate using the formula in equation 9, using an occupancy factor of 0.2 and an absorbed dose conversion factor of 0.7 Sv/Gy for 8760 hours (Shahrokhi et al., 2023).

$$E_{ex}(\mathrm{mSv/y}) = D_{\gamma} \times 0.2 \times 0.7 \times 8760 \quad (9)$$

3.5.3. Annual Committed Effective Dose from water and rice samples

The effective doses (E_w) from surface water samples were estimated as the summation of the ingestion conversion factors (CF_{ing}) expressed in mSv/Bq specific to activities (A_w) of ^{226}Ra (0.00028), ^{228}Th (0.000072) and ^{40}K (0.0000062) in the water samples by applying an annual water consumption rate of 730 litres for adults, as shown in equation 10 (Charles et al., 2024; IAEA, 2014a; Özden, 2024; UNSCEAR, 2000)

$$E_w(\mathrm{mSv/y}) = 730 \times \sum CF_{ing} A_w \quad (10)$$

The Annual Committed Effective Dose (E_r) from the consumption of rice was determined using the expression in equation 11.

$$E_r = C_r \times \sum A_r DCF_{ing} \quad (11)$$

Where A_r is the activity concentration (Bq/kg) in the rice sample, Cr is the annual rice ingestion rate (51 kg/year), and DCF_{ing} is the dose conversion factor; for ^{226}Ra (2.8×10^{-7} Sv/Bq), ^{232}Th (2.3×10^{-7} Sv/Bq) , and ^{40}K (6.2×10^{-9} Sv/Bq) (ICRP, 1996, 2007; UNSCEAR, 2000).

3.5.4. Excess Lifetime Cancer Risk (ELCR)

To assess the likelihood of an individual acquiring cancer during a lifetime as a result of exposure to ionising radiation from naturally occurring radioactive materials (NORMs) in soil and water, the ELCR was estimated using equation 12:

$$\mathrm{ELCR} = E \times DL \times RF \quad (12)$$

where E represents the annual effective dose (mSv/y) in soil or water, DL the duration of exposure (assumed to be 70 years for an average lifespan), and RF is the risk factor for stochastic effects, typically 0.05 per Sv for external exposures and 0.055 per Sv for internal exposures, as

recommended by the ICRP (ICRP, 1990; 2007, WHO, 2017). The estimated ELCR values are then compared with the global average recommended limits, typically 0.29×10^{-3} for external exposure 0.39×10^{-3} for drinking water and generally 1.16×10^{-3} for internal exposure, to assess potential cancer risks to exposed populations (ICRP, 1991; 2007; UNSCEAR, 2008; WHO, 2017). Elevated ELCR values above these limits indicate an increased risk of radiation-induced malignancies, necessitating mitigation measures to reduce public exposure.

3.6. Radionuclides transfer factors and concentration ratios assessment

To establish the contribution of the soil and irrigation water to the migration of the natural radionuclide into rice both the soil-to-plant transfer factor (TF), and irrigation water to rice concentration ratio (CR_W) were determined. These were estimated based on the mean activity concentration in the soils, water and rice samples. The soil-to-plant transfer factor (TF), and irrigation water to rice concentration ratio (CR_W) were determined as the ration of activity concentration in the rice to that in the soil and water activity concentration respectively using equations 13 and 14 (Hossain et al., 2024; Pourimani and Anoosheh 2015; Okeme et al., 2016).

$$TF_i = \frac{A_{r,i}}{A_{s,i}} \tag{13}$$

$$CR_{wi} = \frac{A_{r,i}}{A_{w,i}} \tag{14}$$

Where, $A_{r,i}$ is the activity concentration of radionuclide i in rice (Bq/kg, dry weight), $A_{s,i}$ the activity concentration of radionuclide i in soil within the rooting zone (Bq/kg, dry weight) and $A_{w,i}$ is the activity concentration of radionuclide i in irrigation water (Bq/L)

3.7. Quality Control and Validation

To ensure accuracy and reliability, each sample (soil, water and rice) was assigned a unique identification code for traceability and transported to the laboratory under controlled conditions to prevent alteration or contamination, Background radiation levels were measured and subtracted from sample spectra, Multiple measurements were performed for each sample to minimize random errors. The results were presented as mean ± standard deviation to account for variability and uncertainties and compared with values from international bodies such as UNSCEAR, ICRP, IAEA and WHO to validate consistency.

RESULTS AND DISCUSSION

4.1. Introduction

This chapter presents the results and discussions of the study, corresponding to radionuclide levels in soils from unregulated mining communities, the potential reuse of heap soil pads in building materials and the impact of elevated levels of natural radionuclides on locally cultivated rice irrigated with surface water affected by mining.

4.2. Activity Concentration in Soil samples from the Communities

Table 4.1 shows the mean activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in soil samples collected withing the communities. The mean activity content of ^{238}U is 24±3 Bq/kg, with a range of 5 Bq/kg to 87 Bq/kg. The mean activity concentration of ^{232}Th was determined to be 25±3 Bq/kg, with a range of 5 Bq/kg to 72 Bq/kg, whereas the mean activity concentration for ^{40}K was 328±63 Bq/kg, ranging from 2 Bq/kg to 1168 Bq/kg.

Table 4.1. Results of the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in soil sample within the unregulated mining communities.

Study area	**Activity Concentration, Bq/kg**		
	^{238}U	**^{232}Th**	**^{40}K**
Accra	20±1 (11-32)	43±4 (17-231)	110±20 (68-184)
Ayanfuri	65±2 (29-97)	72±2 (35-117)	1168±68 (500-1796)
Bibiani	10±5 (3-25)	9±7 (1-26)	237±144 (24-580)
Bogosso-Prestea	87±8 (4-235)	39±2 (27-51)	345±91 (320-360)
Bui Dam (sediment)	5±1 (2-10)	5±1 (3-7)	129±24 (98-133)
Dunkwa-on-Offin	25±1	29±6	226±94

	(11-45)	(10-68)	(96-409)
Kenyasi	15±6 (8 – 26)	27±8 (9 -67)	157±16 (60 – 249)
Konongo-Odumase	9±1 (2-17)	22±1 (2-37)	200±4 (39-407)
Lake Bosomtwi (sediment)	8±1 (7-10)	6±1 (5-8)	276±22 (226-304)
New Abirim	12±1 (5-21)	11±2 (3-24)	140±25 (24-426)
New Juaben	13±3 (6-18)	11±3 (6-17)	206±30 (87-344)
Nkrofo	8 ± 1 (7-16)	44 ± 1 (13–87)	395 ± 123 (284-508)
Obuasi	43±8 (29-52)	33±6 (25-44)	632±142 (582-736)
River Pra (sediment)	25±2 (8-42)	28±6 (4-55)	233±67 (85-479)
Tarkwa	42±4 (35-49) 730±241 *a* (557-898) 37± 1 *b* (36-38)	30±5 (21-37) 460± 226 *a* (297-617) 30± 1 *b* (29-30)	682±134 (618-694) 48±3 *a* (38-57) 2± 1 *b* (2-3)
Tema	7±1 (5-9) 11±1 *c* (10-32)	17±3 (13-16) 33±3 *c* (17-231)	62±9 (78-110) 95±19 *c* (68-184)
Tono Irrigation dam (sediment)	7±1 (5-9)	7±1 (6-8)	380±95 (219-453)
Mean	**24±3** *d* **61±16** *e*	**25±3** *d* **49±15** *e*	**328±63** *d* **296±57** *e*

Range	**5-87**	**5-72**	**2-1168**
World Mean Value (USNCEAR, 2000)	**33**	**45**	**420**

[a] Sludge; [b] Scales; [c] soil from oil refinery premises; [d] excluding result of the sludges and scales; [e] including results from the sludges and scales; MDA: ^{238}U (1 Bq/kg), ^{232}Th (1 Bq/kg), ^{40}K (2 Bq/kg)

The results presented in Table 4.1 shows that the sludge samples recorded the most activity concentrations of ^{238}U and ^{232}Th, thereby indicating that these elements are the predominant natural radionuclides in all the present study samples and serving as an accumulation sink for ^{238}U and ^{232}Th. In addition to the sludge samples, substantial activity levels of natural radionuclides were also recorded in samples from Ayanfuri and Obuasi. Excluding the results of the sludges and scales would result in a mean activity of ^{238}U and ^{232}Th and ^{40}K well below the world mean values as well as below the exemption values and all together does not necessitate for remedial action or regulatory control (UNSCEAR, 2000). However, including the results of the sludges and scales will results in an overall mean concentration of ^{238}U and ^{232}Th elevated above the world mean values. This shows significant influence of the sludges and scales, otherwise known as TENORM have on the natural radionuclide concentration in the environment and highlight the need for these TENORM to be properly manages.

4.2.1. Statistical descriptivism and predictivity of ^{238}U, ^{232}Th, and ^{40}K concentrations in the soil samples

In accordance with the data presented in Table 4.1, the statistical descriptivism and predictivity of the radionuclides are presented in Table 4.2 and Table 4.3.

Table 4.2. The descriptive statistical analysis of the soil samples results.

Statistical Measurement	**^{238}U (Bq/kg)**	**^{232}Th (Bq/kg)**	**^{40}K (Bq/kg)**
Count	17	17	17
Average	24	25	328
Standard deviation	22	17	275

Minimum	5	5	62
Q1	8	11	157
Q2 (Median)	13	27	233
Q3	25	33	380
Maximum	87	72	1168
Range	82	67	1106
Variance	536	322	75935
IQR	17	22	223

Count: Quantity of observations; **Average:** The arithmetic mean; **Standard deviation:** a metric quantifying the degree of variance or dispersion within a dataset; **Minimum:** The least value; **Q1:** 1st quartile, an indicator of the value under which 25% of data set are found when arranged in increasing order; **Q2 (Median):** 2nd quartile, an indicator of centre tendency for skewed distributions (50%) when arranged in increasing order; **Q3:** 3rd quartile, an indicator of the value under which 75% of data set are found when arranged in increasing order; **Maximum:** The highest value; **Range:** The difference between the maximum and minimum values; **Variance:** A quantification of the dispersion of data; **IQR:** Interquartile Range, measuring the centre at 50% of the data.

A one-way analysis of variance (ANOVA) was used to determine if there were statistically significant differences in the activity concentrations of the natural radionuclides ^{238}U, ^{232}Th, and ^{40}K in the soil samples collected from the different locations. This method tests whether the mean activity concentrations differ significantly by partitioning the total variability of the data into between-group and within-group components via the expression (Montgomery, 2017):

$$Y_{ij} = \mu + \tau_i + \epsilon_{ij}$$

where Y_{ij}represents the measured activity concentration of the radionuclide, μ is the overall mean activity concentration, τ_i is the effect of the i^{th}group, and $\epsilon_{ij}$is the random error associated with the observation. Statistical significance was evaluated using the F-statistic, which is calculated using the expression,

$$F = \frac{MS_{between}}{MS_{within}}$$

where $MS_{between}$ and MS_{within} are the mean squares between groups and within groups, respectively (Montgomery, 2017). The statistical significance was considered at a 95% confidence level ($p < 0.05$). The outcomes of the analysis of variance (ANOVA) tests for each natural radionuclides in the soil are presented in Table 4.3.

Table 4.3. The ANOVA analysis of the natural radionuclide in the soil

	^{238}U	^{232}Th	^{40}K
F-Value	0.85	1.03	0.89
P-Value	0.58	0.48	0.56

The p-values in every instance exceed the conventional alpha level of 0.05, thereby indicating the absence of statistically significant disparities in the levels of ^{238}U, ^{232}Th, and ^{40}K across the various study areas under investigation.

To establish a relationship and/or deduce a pattern from the results of the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in the soil samples, an inferential statistical regression analysis was conducted. The regression analysis performed on the dataset used a conventional approach, employing the concentration of a single element to predict that of another. In light of the inherent properties of the data, a suite of multiple linear regression models was implemented, with the objective of elucidating the interrelationships between the concentrations of the radionuclides. This was intended to determine the level of predictability of ^{238}U concentration based on ^{232}Th and ^{40}K concentrations, the ^{232}Th concentration based on ^{238}U and ^{40}K concentrations, and the ^{40}K concentrations based on ^{238}U and ^{232}Th concentrations. The regression analysis results show that 80.6% of the fluctuation in ^{238}U concentration accounted for by the ^{232}Th and ^{40}K concentrations, with both positively correlated and ^{40}K being statistically significant ($P<0.05$). For predicting ^{232}Th concentration based on ^{238}U and ^{40}K, the model explains 76.9% of the variability, with positive correlations for both and ^{238}U showing statistical significance ($P<0.05$). Similarly, predicting ^{40}K concentration from ^{238}U and ^{232}Th also explains 76.9% of the variability, with positive correlations for both, but only ^{238}U coefficient is statistically significant ($P<0.05$). Scatter plots with regression lines were generated for each pair of radionuclides, as illustrated in Figure 4.1.

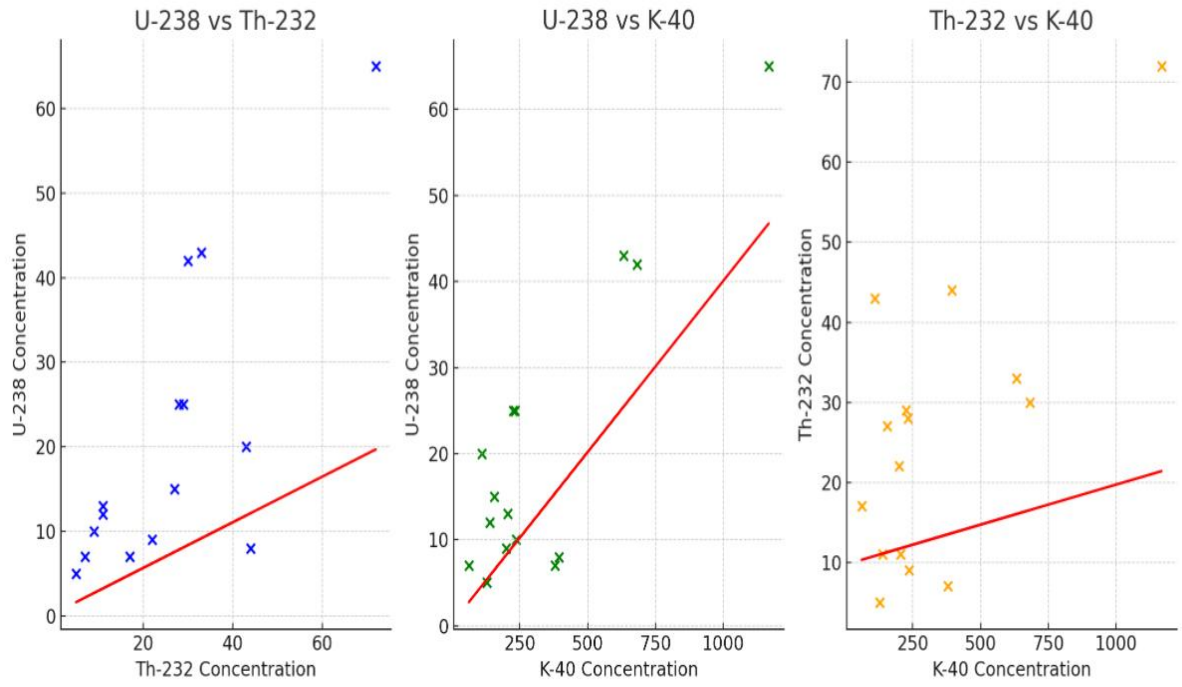

Figure 4.1. Scatter plot with the regression lines of the radionuclide's concentrations in soil.

These findings indicate the presence of a substantial correlation within these naturally occurring radionuclides in the soil samples. The relatively elevated R-squared values imply that a substantial shared fluctuation in each radionuclide concentration can be attributed to the two other radionuclides. Nonetheless, it is imperative to analyse these findings with prudence, as the fundamental causal processes may be intricate and above the frame of a basic linear regression analysis.

Figure 4.2 shows the concentrations of ^{238}U, ^{232}Th and ^{40}K in three-dimensional space. Each data point in the figure corresponds to a specific sample together with its corresponding concentrations for the three radionuclides, thereby providing a thorough perspective on the interrelationships between these elements' concentrations within the dataset.

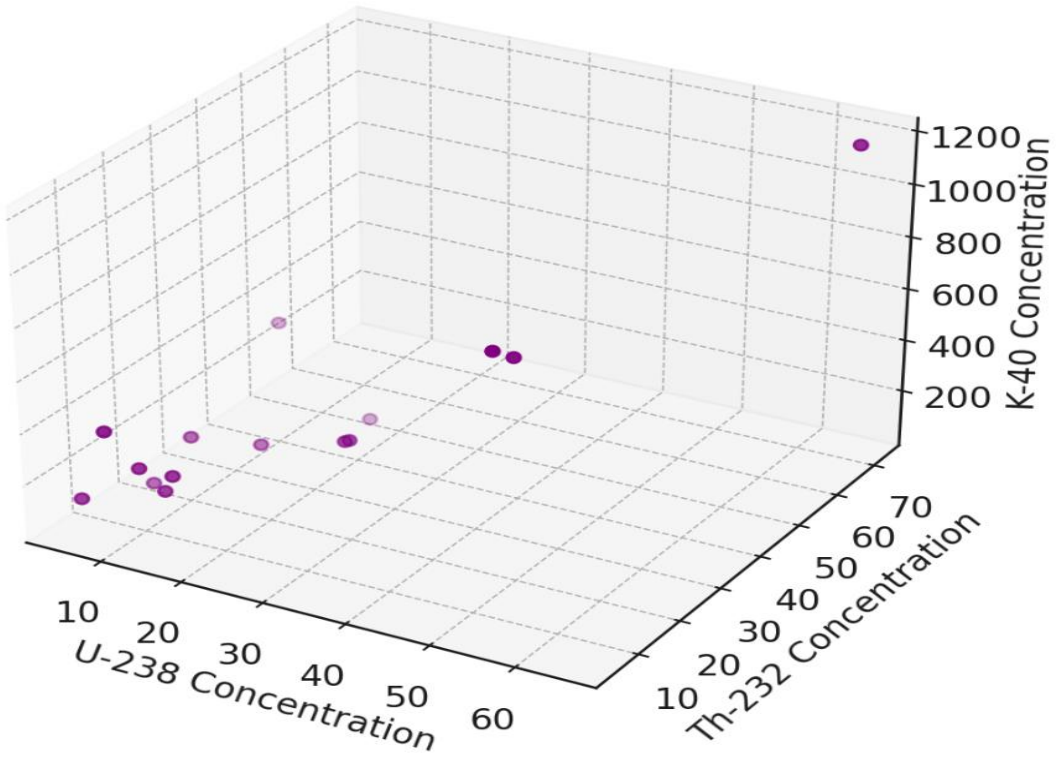

Figure 4.2. Three-dimensional scatter plot to illustrate the correlations among radionuclides in soil.

4.2.2. Radiological Hazard Indices in respect of the soil samples from the mine communities

As shown in Table 4.4, the findings of the radiological risk are presented, including the activity of radium equivalent (Ra_{eq}), the gamma index (I_γ), absorbed dose rate (D_γ), external hazard index (H_{ex}), internal hazard index (H_{in}), and the estimated indoor annual effective doses (E_{ex}) as well as the corresponding Excess Lifetime Cancer Risk due to external exposure. The study aimed to assess if soil samples from the specified sites could present a danger of public radiation exposure if utilised as construction materials. The evaluation of radiation risks in construction materials entails the analysis of the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K (Beretka and Mathew, 1985). In theory, the activity of ^{238}U is in equilibrium with ^{226}Ra in soil samples. Hence, ^{226}Ra can be utilised as a proxy for ^{238}U, given that roughly 98.5% of the radioactive risk from the uranium series derives from radium and its decay products, especially radon. Therefore, the estimated activity of ^{238}U can be used to assess the radiological risk.

The mean radium equivalent activity of the soil was determined to be 85±12 Bq/kg, along with the associated absorbed dose rate, gamma index, external hazard index, and internal hazard index of 40±6 nGy/h, 0.32±0.11, 0.23±0.03, and 0.29±0.04, respectively. It is evident from the data presented in Table 4.4 that the annual effective doses calculated with a mean 0.05±0.01 mSv/y are considered to be of negligible significance when placed in relation to the global annual construction guidance limit of 1 mSv/y although for some areas considered relatively high for public exposure limes of 0.07 mSv/y (IAEA 2014a; UNSCEAR, 2000). This result excluded the results from the sludges and scales in the computation as these are naturally NORM residue which are normally not incorporated into building or construction materials as they are known to contain elevated activity concentration of natural radionuclide as evident in the results. Almost all of soil samples in this study are radiologically appropriate for use as construction materials, as their radiological hazard indices remain below the set thresholds. While the soils from Ayanfuri, Bogosso-Prestea, and Obuasi shows elevated indices in comparison to the other soil samples, nonetheless apart from the gamma absorbed dose rate, they were relatively below the guidance limit (see Table 4.4). However, this is not the case for sludge and scale samples. It is thus advisable that in the absence of continuous onsite regulatory monitoring onshore and offshore, these wastes are appropriately stored or disposed of, to prevent their unintentional incorporation into construction materials.

Table 4.4. Estimated absorbed dose rates, radium equivalent activities, gamma, external and internal hazard indices, the indoor annual effective doses, and ELCR due to ^{238}U, ^{232}Th and ^{40}K in soil samples.

Study area	D_γ (nGy/h)	Ra_{eq}, (Bq/kg)	I_γ	H_{ex}	H_{in}	E_{ex} (mSv/y)	ELCR x10^{-3}
Accra	40±4	90±8	0.32±0.03	0.24±0.02	0.30±0.03	0.05±0.01	0.17
Ayanfuri	122±5	258±10	0.97±0.04	0.70±0.03	0.87±0.03	0.15±0.01	0.52
Bibiani	20±13	41±26	0.16±0.10	0.11±0.07	0.14±0.08	0.02±0.02	0.09
Bogosso-Prestea	78±9	169±18	0.60±0.07	0.46±0.05	0.69±0.07	0.10±0.01	0.34
Bui Dam	11±2	22±4	0.08±0.02	0.06±0.01	0.07±0.01	0.01±0.01	0.05
Dunkwa-on-Offin	38±8	84±17	0.30±0.06	0.23±0.05	0.29±0.05	0.05±0.01	0.17
Kenyasi	30±8	66±19	0.24±0.07	0.18±0.05	0.22±0.07	0.04±0.01	0.13
Konongo-Odumase	26±1	56±3	0.21±0.01	0.15±0.01	0.18±0.01	0.03±0.01	0.11
Lake Bosomtwi	19±2	38±4	0.15±0.02	0.10±0.01	0.12±0.01	0.02±0.01	0.08
New Abirim	18±3	39±6	0.14±0.02	0.11±0.02	0.14±0.02	0.02±0.01	0.08
New Juaben	21±4	45±10	0.17±0.04	0.12±0.03	0.16±0.03	0.03±0.01	0.09
Nkrofo	47±6	101±12	0.38±0.05	0.27±0.03	0.30±0.03	0.06±0.01	0.20
Obuasi	66±13	139±28	0.52±0.10	0.38±0.07	0.49±0.10	0.08±0.02	0.28
River Pra	38±7	83±16	0.30±0.06	0.22±0.04	0.29±0.05	0.05±0.01	0.16

Tarkwa	66±10 617±249 [a] 35±1 [b]	137±21 1391±566 [a] 80±2 [b]	0.52±0.08 4.75±1.3 [a] 0.27±0.04 [b]	0.37±0.06 3.76±1.52 [a] 0.22±0.01 [b]	0.48±0.07 5.73±2.17 [a] 0.32±0.01 [b]	0.08±0.01 0.76±0.30 [a] 0.04±0.01 [b]	0.28 2.65 [a] 0.15 [b]
Tema	16±3 29±4 [c]	36±6 66±8 [c]	0.13±0.02 0.23±0.08 [c]	0.10±0.02 0.18±0.02 [c]	0.12±0.02 0.21±0.02 [c]	0.02±0.01 0.04±0.01 [c]	0.07 0.12 [c]
Tono Irrigation dam	23±5	46±10	0.19±0.04	0.12±0.03	0.14±0.03	0.03±0.01	0.10
Mean	**40±6** [d] **68±31** [e]	**85±12** [d] **149±38** [e]	**0.32±0.05** [d] **0.53±0.05** [e]	**0.23±0.03** [d] **0.40±0.11** [e]	**0.29±0.04** [d] **0.56±0.15** [e]	**0.05±0.01** [d] **0.26±0.03** [e]	**0.17** [d] **0.29** [e]
Range	**11-122**	**22-258**	**0.08-0.97**	**0.06-0.70**	**0.07-0.87**	**0.01-0.15**	**0.05-0.52**
Limits (IAEA 2014a, 2014b; UNSCEAR, 2000)	**60**	**370**	**1**	**1**	**1**	**0.07** [f] **1** [g]	**0.29**

[a] Sludges; [b] Scales; [c] soil from oil refinery premises; [d] excluding result of the sludges and scales; [e] including results from the sludges and scales; [f] public exposure Limit; [g] construction limit

4.3. Activity Concentration of ^{226}Ra, ^{228}Th and ^{40}K in the water samples collected within the communities

Table 4.5 shows the estimated concentrations of ^{226}Ra, ^{228}Th and ^{40}K in the surface water samples and the gross alpha and gross beta screening results of water from borehole and/or hand dug wells which were collected within the community. The mean activity concentrations of ^{226}Ra, ^{228}Th and ^{40}K in the surface water samples are presented, along with their respective annual committed effective doses, the corresponding ELCR.

Excluding the activity concentrations of the water sampled from the oil refinery which is not for domestic use, the mean values for ^{226}Ra, ^{228}Th and ^{40}K of the sampled surface water were determined to be 1.15±0.21 Bq/L (ranging from 0.15 Bq/L to 4.72 Bq/L), 1.60±0.43 Bq/L (range: <MDA–6.40 Bq/L), and 20.70±3.32 Bq/L (ranging from 0.34 Bq/L to 166.74 Bq/L), respectively. The concentrations of ^{226}Ra and ^{228}Th in the water samples was found to be just relatively lower than the concentration recommended by the World Health Organization (WHO, 2017) of 1 Bq/L as shown in Table 4.5 except at Bogosso-Prestia, Dunkwa-on-Offin, Konongo-Odumasi, River Pra and at Tono irrigation dam were the concentrations surpassed the recommended guidance limit. This disparity can be ascribed to the comparatively positive recharge of the ^{226}Ra and ^{228}Th concentration from ^{238}U and ^{232}Th respectively via washout from the soils as a result of the unregulated mining activities within the study area. The relative levels of ^{40}K may be attributed to washout from farms lands that used fertilizers on their lands especially for the study areas including Bogosso-Prestea, Dunkwa-on-Offin, Konongo-Odumase, and Tono irrigation dame are known for extensive farming. Evidently these surface waters present have some level of radiological health risk if used for domestic purposes over an extended period of time. Likewise, there may be trace representation of some of these natural radionuclides in plants root uptake especially for those plants that are irrigated with water from these sources.

Table 4.5. Results of the activity, effective dose, ELCR, surface water and gross alpha, and gross beta activity of borehole/hand-dug-well water within the unregulated mining communities.

Study area	Activity Concentrations, Bq/L			E_w (mSv/y)	ELCR x10^{-3}	Gross Alpha and Gross Beta Activity Concentration (Bq/L)	
	^{226}Ra	^{228}Th	^{40}K			Gross Alpha	Gross Beta
Accra	0.23±0.04 (0.05-0.21)	0.51±0.04 (<MDA -0.94)	0.34±0.04 (0.20-0.55)	0.08±0.01 (0.03-0.10)	0.29	0.002	0.01
Ayanfuri	0.16±0.01 (0.11-0.23)	0.45±0.08 (0.23-0.58)	0.75±0.02 (0.64-0.89)	0.06±0.01 (0.04-0.08)	0.23	0.005	0.05
Bibiani	0.86±0.07 (0.13-2.87)	0.97±0.33 (0.37-4.29)	9.05±1.45 (0.10-31.73)	0.27±0.04 (0.03-0.96)	1.03	0.002	0.04
Bogosso-Prestea	3.21±0.44 (2.09-7.86)	6.40±2.40 (3.12-9.58)	42.50±8.00 (27.28-49.83)	1.18±0.25 (0.71-2.34)	4.56	0.004	0.08
Bui Dam	0.26±0.01 (0.13-0.42)	0.47±0.20 (0.07-0.82)	1.60±0.30 (0.78-2.42)	0.09±0.01 (0.07-0.14)	0.33	0.002	0.09
Dunkwa-on-Offin	4.72±1.51 (1.01-7.03)	2.70±0.40 (2.10-3.50)	53.90±11.60 (19.80-62.20)	1.35±0.38 (0.41-1.90)	5.20	0.006	0.05
Kenyasi	0.54±0.03 (0.11–1.03)	0.41±0.10 (0.21 – 0.56)	7.76±2.70 (1.65 – 11.99)	0.17±0.02 (0.04-0.29)	0.64	0.003	0.01
Konongo-Odumase	1.59±0.51 (0.74-3.08)	4.44±2.11 (2.71-11.79)	14.39±3.76 (7.74-18.65)	0.62±0.23 (0.33-1.33)	2.40	0.005	0.02

Lake Bosomtwi	0.78±0.02 (0.09-2.15)	0.19±0.10 (0.03-0.86)	8.76±2.40 (1.24-15.49)	0.21±0.02 (0.03-0.55)	0.80	0.003	0.04
New Abirim	0.38±0.06 (0.16-1.47)	0.55±0.01 (0.12-2.21)	2.06±0.43 (0.16-7.31)	0.12±0.01 (0.04-0.45)	0.45	0.005	0.04
New Juaben	0.23±0.02 (0.18-0.29)	0.57±0.04 (0.37-0.68)	0.34±0.08 (0.25-0.48)	0.08±0.01 (0.06-0.14)	0.30	0.001	0.02
Nkrofo	0.15±0.03 (0.10-0.20)	0.98±0.04 (0.70-1.52)	0.76±0.06 (0.61-0.93)	0.09±0.01 (0.06-0.12)	0.33	0.001	0.04
Obuasi	0.32±0.02 (0.15-0.46)	0.94±0.05 (0.76-1.33)	0.69±0.04 (0.52-0.87)	0.12±0.01 (0.07-0.17)	0.45	0.002	0.03
River Pra	2.51±0.70 (1.38–4.01)	1.71±0.49 (1.02–2.85)	41.43±5.83 (29.40–47.77)	0.79±0.20 (0.47-1.19)	3.04	0.003	0.05
Tarkwa	0.24±0.04 (0.07-0.42)	0.90±0.06 (0.65-1.12)	0.54±0.05 (0.41-0.81)	0.10±0.01 (0.05-0.15)	0.38	0.005	0.04
Tema	0.15±0.04 (0.05-0.22) 8.32±1.56 [a] (7.08-12.42)	0.51±0.04 (0.35-0.98) 8.70±1.60 [a] (7.93-9.40)	0.35±0.04 (0.21-0.52) 28.56±7.20 [a] (26.94-31.70)	0.06±0.01 (0.03-0.10) N/A	0.23 N/A	0.005 N/A	0.03 N/A
Tono Irrigation dam	3.17±0.57 (2.36-4.16)	4.46±0.89 (2.68-5.48)	166.74±14.55 (133.24-175.87)	1.64±0.23 (1.23-1.93)	6.30	0.007	0.06
Mean	**1.15±0.21***	**1.60±0.43***	**20.70±3.32***	**0.41±0.08***	**1.59***	**0.004**	**0.04**

Range	**0.15-4.72**	**<MDA-6.40**	**0.34-166.74**	**0.06-1.64**	**0.23-6.30**	**0.001-0.007**	**0.01-0.09**
Guideline levels (IAEA, 2014a, 2014b; ICRP, 2007; WHO, 2017;)	**1.00**	**1.00**	**N/A**	**0.10**	**0.39**	**0.500**	**1.00**

[a] sample from oil refinery site; * does not include results from the oil refinery since it not for consumption; N/A not applicable.

MDA: ^{226}Ra (0.05 Bq/L), ^{228}Th (0.05 Bq/L), ^{40}K (0.10 Bq/L)

4.3.1. Statistical descriptivism and predictivity of water sample results

As illustrated in Table 4.6 and Table 4.7, the statistical descriptivism, and the results of a one-way analysis of variance (ANOVA) for the quantified radionuclides in the surface water samples within the unregulated mining communities are presented. The ANOVA text determined whether there was statistically significant disparity in the activity concentrations in the surface water samples collected from different locations at a 95% confidence level ($p < 0.05$).

Table 4.6. The descriptive statistical analysis of the water samples results.

Statistical Measurement	^{226}Ra (Bq/L)	^{228}Th (Bq/L)	^{40}K (Bq/L)	E_w (mSv/y)	ELCR
Count	17	17	17	17	17
Average	1.15	1.60	20.70	0.41	1.59
Standard deviation	2.21	2.48	41.06	0.68	2.37
Minimum	0.15	0.19	0.34	0.06	0.23
Q1	0.26	0.47	1.60	0.09	0.30
Q2 (Median)	0.54	0.94	7.76	0.17	0.58
Q3	2.51	1.71	41.43	0.79	2.77
Maximum	4.72	6.40	166.74	1.64	6.30
Range	5.80	6.55	154.05	1.69	5.90
Variance	3.46	4.72	1560.98	0.35	4.27
IQR	1.61	1.68	25.75	0.53	1.87

Count: Quantity of observations; **Average:** The arithmetic mean; **Standard deviation:** a metric quantifying the degree of variance or dispersion within a dataset; **Minimum:** The least value; **Q1:** 1st quartile, an indicator of the value under which 25% of data set are found when arranged in increasing order; **Q2 (Median):** 2nd quartile, an indicator of centre tendency for skewed distributions (50%) when arranged in increasing order; **Q3:** 3rd quartile, an indicator of the value under which 75% of data set are found when arranged in increasing order; **Maximum:** The highest value; **Range:** The difference between the maximum and minimum values; **Variance:** A quantification of the dispersion of data; **IQR:** Interquartile Range, measuring the centre at 50% of the data.

The results of the analysis of variance (ANOVA) demonstrate that, for all evaluated variables, there are no significant differences in the mean values across the various research locations. The uniformity suggests that there is a relative homogeneity of the radionuclides and their possible health implications along the communities. Additionally, the findings suggest that there is no significant statistically variation in the mean activity concentrations and committed doses across the study areas, as evidenced by the high p-values.

Table 4.7. The ANOVA analysis of the natural radionuclide in the surface water

	^{226}Ra	^{228}Th	^{40}K
F-Value	0.089	0.128	4.453
P-Value	0.996	0.986	0.358

In applying a multiple linear regression analysis to determine the predictability of each radionuclide, the regression analysis shows that 76.5% of the fluctuations in ^{226}Ra concentration can be explained by ^{228}Th and ^{40}K concentrations, with both positively correlated; a unit increase in ^{228}Th raises ^{226}Ra by 0.745 units, and a unit increase in ^{40}K raises ^{226}Ra by 0.004 units. Similarly, the regression analysis for predicting ^{228}Th concentration based on ^{226}Ra and ^{40}K concentrations shows an R-squared value of 0.765, suggesting that 76.5% of the fluctuations in ^{228}Th concentration is explained by these variables. However, both ^{226}Ra and ^{40}K concentrations are positively correlated with ^{228}Th, with a 0.935-unit increase in ^{228}Th for each unit increase in ^{226}Ra, and a 0.005-unit increase for each unit increase in ^{40}K. In contrast, predicting ^{40}K concentration from ^{226}Ra and ^{228}Th concentrations yields an R-squared of 0.240, showing that only 24.0% of the variability in ^{40}K is explained by these factors. Despite this lower explanatory power, positive correlations exist, with a 4.660-unit increase in ^{40}K per unit increase in ^{226}Ra and a 4.247-unit increase in ^{40}K per unit increase in ^{228}Th. The results obtained suggest the presence of a significant relationship among the natural radionuclides concentrations in the surface water. The elevated R-squared values in the initial two models signify that considerable fluctuations in the concentration each radionuclide can be attributed to the other two radionuclides. The last model, however, possesses a comparatively lower R-squared value, signifying diminished predictive capability. Even though these findings present an understanding into the interrelationships of various factors, it is however, crucial to acknowledge that fundamental causal processes may be intricate and above

the frame of a basic linear regression analysis, necessitate further investigation beyond basic linear regression.

As demonstrated in Figure 4.3, the relationship between two radionuclides is evident. These figures offer a graphical depiction of the correlation among two radionuclides, highlighting emphasising the fluctuations in their concentrations relative to one another throughout the research regions. However, as demonstrated in Figure 4.4, there is a clear correlation between the concentrations of ^{228}Th, ^{40}K, and ^{226}Ra. Each blue dot in the graphic is a data point from the dataset, representing each of the radionuclides in a three-dimensional plane. The concentrations of ^{228}Th and ^{40}K collectively provide a quantitative basis for understanding the relationship between the concentration of ^{226}Ra in the specified dataset.

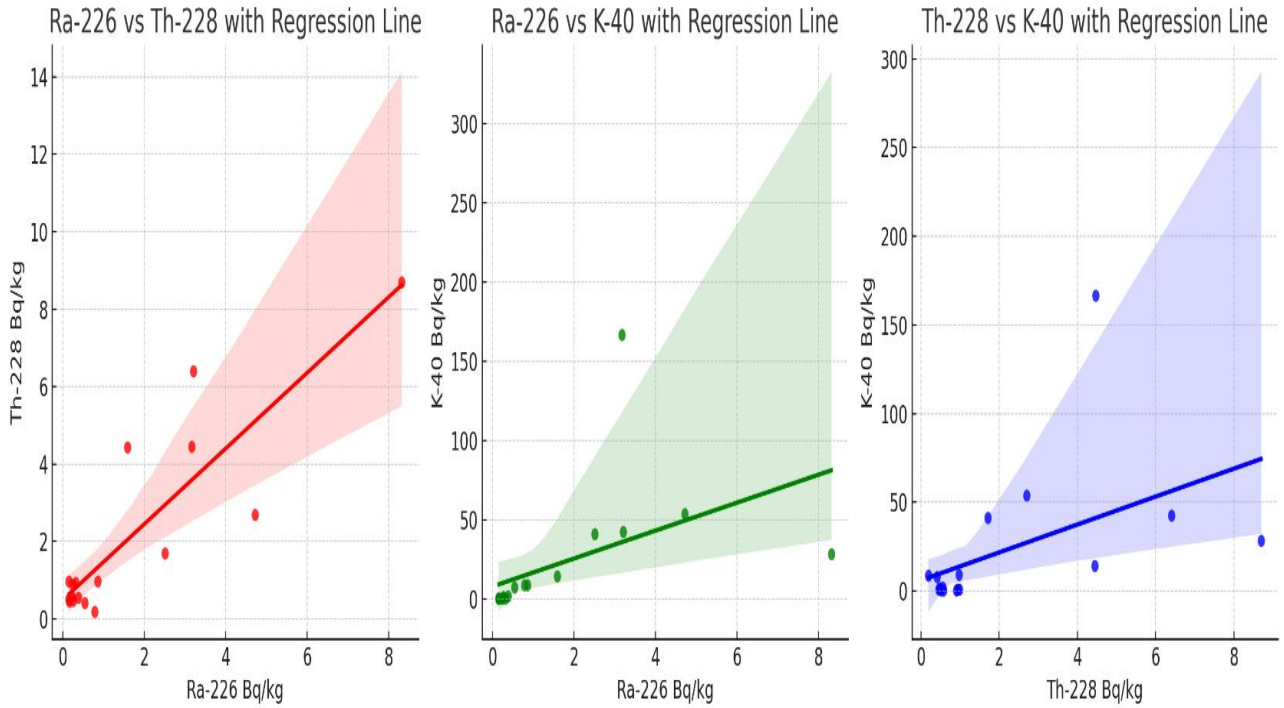

Figure 4.3. Scatter plot with the regression lines of the radionuclide's concentrations in surface water.

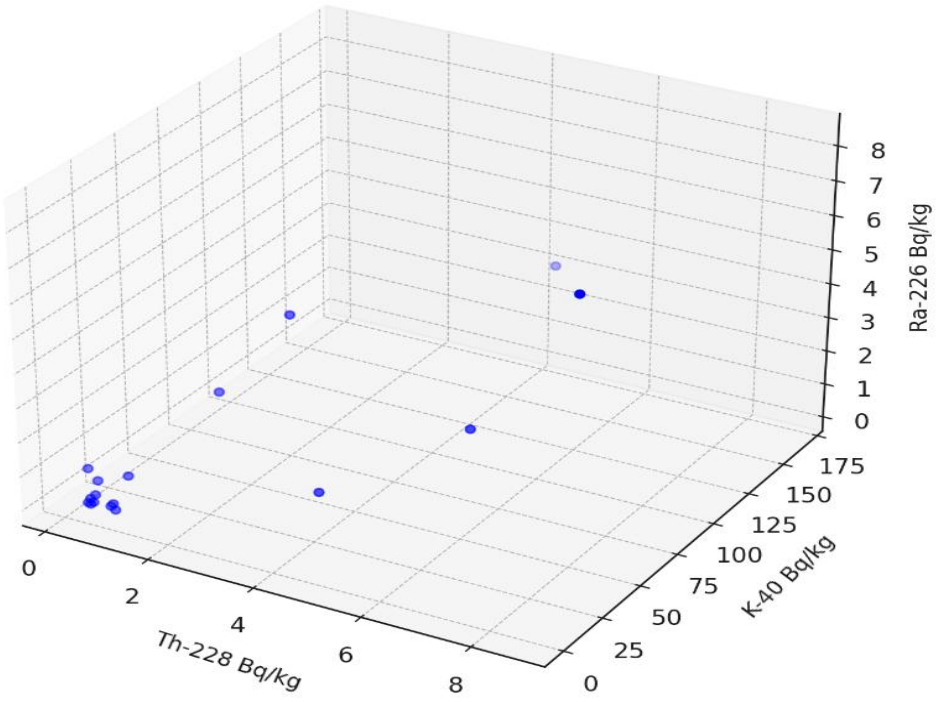

Figure 4.4. Three-dimensional scatter plot to illustrate the correlations among radionuclides in surface water.

As evidenced by the findings of this study, the elevated concentrations of ^{228}Th relative to ^{226}Ra are potentially ascribable to the disparity in solubility between the two elements or a possible washout form the soils into the water bodies. Furthermore, the absence of filtration of the water samples prior to analysis may have had a bearing on the findings. It is acknowledged that thorium is transported by particulate matter and has a propensity to precipitate or settle at the bottom of water bodies. Consequently, the existence of particle matter in the water samples could be a contributing factor to the elevated activity concentrations of ^{228}Th. It is imperative to comprehend these factors in order to accurately monitored and interpret radionuclide concentrations in surface water, and their ramifications for environmental and public radiation protection.

4.3.2. Radiological Hazard risk assessment of the water samples within the unregulated mining communities

From Table 4.5, the mean annual committed effective dose resulting from the surface water concentrations was ascertained as 0.41±0.08 mSv/y, with a range of 0.06 mSv/y to 1.64 mSv/y. It

is noteworthy that from Figure 4.5, The mean annual committed effective dose of 0.41 mSv/y from the surface water samples is over four times greater than the suggested guideline limit of 0.1 mSv/y set by the WHO and the ICRP but does not require any remedial action unlike for samples that were taken from Bogosso-Prestea, Dunkwa-on-Offin and the Tono irrigation dam (IAEA, 2014a; ICRP, 2007; WHO, 2004).

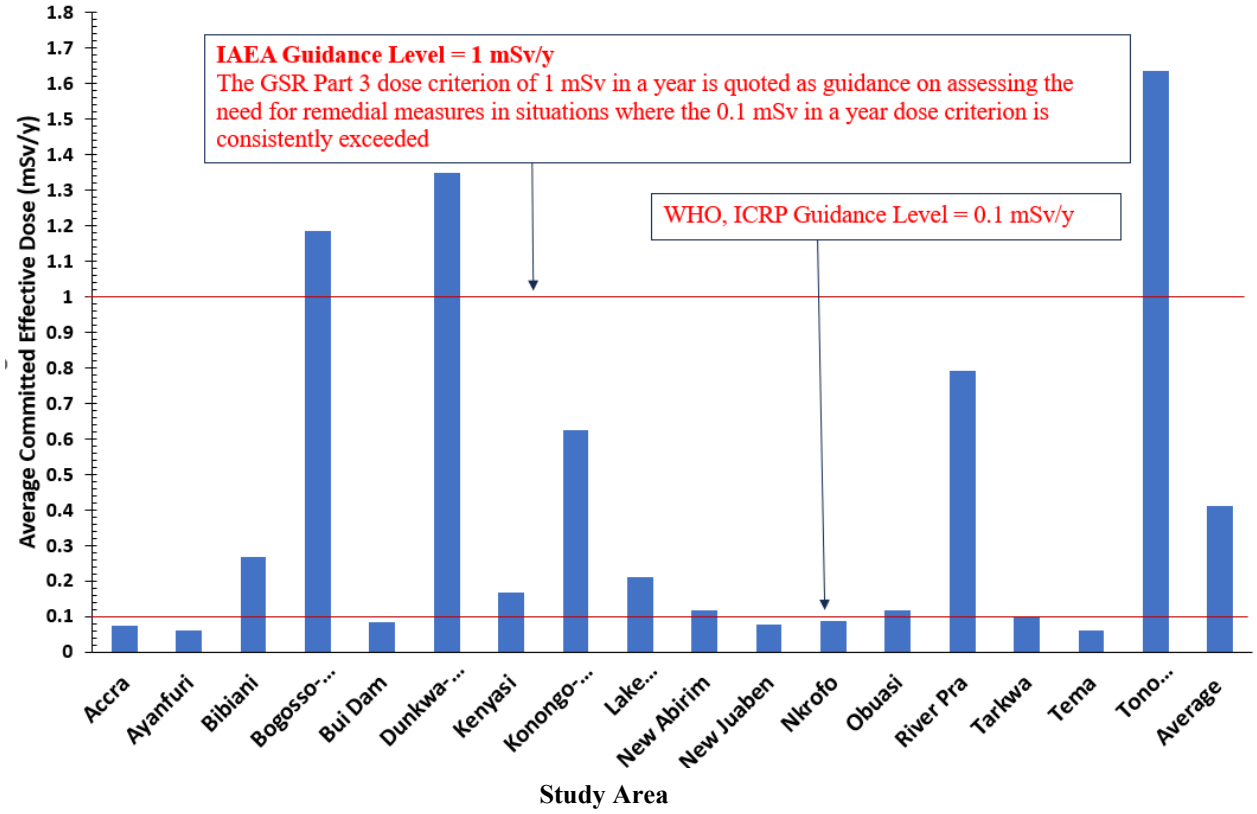

Figure 4.5. Distribution of the annual committed effective dose across the study areas

This finding suggests that the surface water resources with the unregulated mining communities has elevated levels of natural radionuclides, which pose a substantial radiation hazard to the members of the communities who uses these surface water resource if it is not treated. The elevated NORM activities concentration with corresponding significant mean committed effective dose recorded in these communities are presumably attributable to the fact that the majority of communities where the study was conducted is prevalent with illegal mining and water source pollution from the mining activities. As anticipated, water samples collected within the oil refinery location exhibited elevated concentrations of radium and thorium concentrations in addition to

other observable elevation at most of the sample area. Since majority of the water sources examined in this study are readily available for domestic and agriculture use, it is therefore essential that these surface water resources are monitored, and effective treatment measures are implemented to alleviate latent public health risks.

4.3.3. Gross alpha and gross beta screening of boreholes and a hand-dug well within the unregulated mining communities

This study measured the concentrations of gross alpha and beta activity across different boreholes and a hand-dug well. There were notable variations among the sampling areas as shown in Table 4.5 and Figure 4.6. However, none exceeded the Ghana Standard Authority (GSA) recommended limits of 0.1 Bq/L and 1.0 Bq/L for gross alpha and beta, respectively, nor the WHO recommended limits of 0.5 Bq/L and 1.0 Bq/L for gross alpha and beta, respectively.

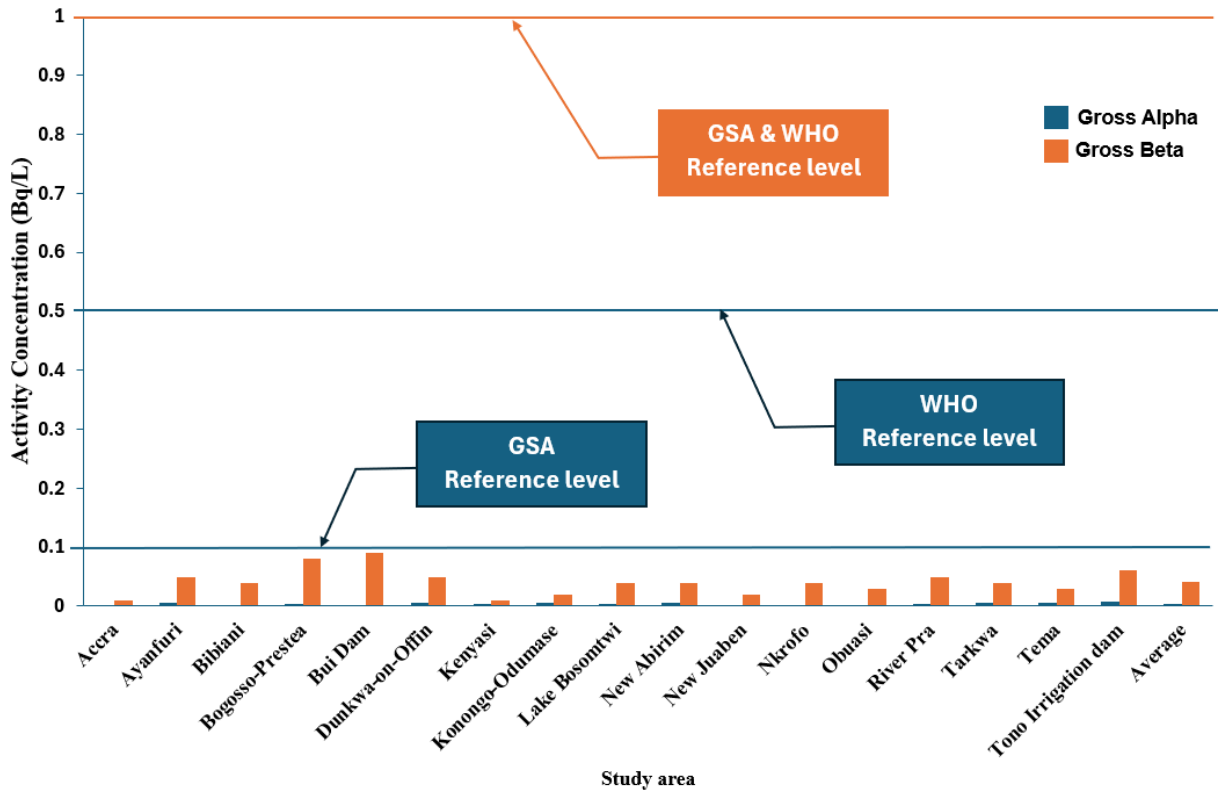

Figure 4.6. Gross Alpha and Beta screen of boreholes and hand-dug wells withing the study areas

This indicates that there is no observable contamination from naturally occurring radioactive materials, such as uranium and thorium decay products (IAEA, 2014a, 2014b; Vinson et al., 2009; WHO, 2011, 2017). Comparisons with similar studies in other regions suggest that, although some samples exceed global safety limits, the majority fall within acceptable ranges. For example, studies of groundwater sources in areas with high background radiation, such as Kerala in India and Ramsar in Iran, have reported significantly higher gross alpha and beta activities due to increased uranium and thorium deposits (Sohrabi, 2013). Conversely, regions with lower concentrations of geological radionuclides tend to exhibit minimal gross alpha and beta activity, consistent with findings in less affected areas of this study (Tzortzis and Tsertos, 2004). Given these results, it is essential to continuously monitor and periodically screen drinking water sources to mitigate potential radiation exposure risks. Where elevated gross alpha or beta activity is observed, further radionuclide-specific analysis is recommended to identify the contributing isotopes and implement appropriate remediation measures (IAEA, 2014a).

4.4. ELCR due from the Soil and Water Samples

As demonstrated in Table 4.4, and Table 4.5, the estimated ELCR exhibited significant variations in values across different sample locations. Specifically, certain sample locations demonstrated exceedingly high values, while others exhibited comparatively low values. The ELCR values varied from 0.05×10^{-3} to 0.52×10^{-3}, with a mean of 0.17×10^{-3} in the soil, and that from the surface water varied from 0.23×10^{-3} to 6.30×10^{-3}, with a mean of 1.59×10^{-3}, while excluding the estimated values from the sludges, scales and water from the oil refinery.

As shown in and Figure 4.7, while the mean ELCR value of the soil was below the recommended guidance level of 0.29×10^{-3}, those from Ayanfuri, and Bogosso-Prestea were above the recommended level and hence people in these two communities have an increased risk of developing cancer in these areas due to exposure from the soil. On the contrary, the mean ELCR value of the surface water samples are approximately 4.07 more than the recommended values and 0.39×10^{-3}, with some of the areas exhibiting far greater values as shown in Figure 4.7. The population in locations with elevated ELCR values are at an increased risk of developing cancer in these areas due to committed exposure from the surface water. It is therefore inadvisable for the surface water sources to be consumed as drinking water or used for domestic purposes.

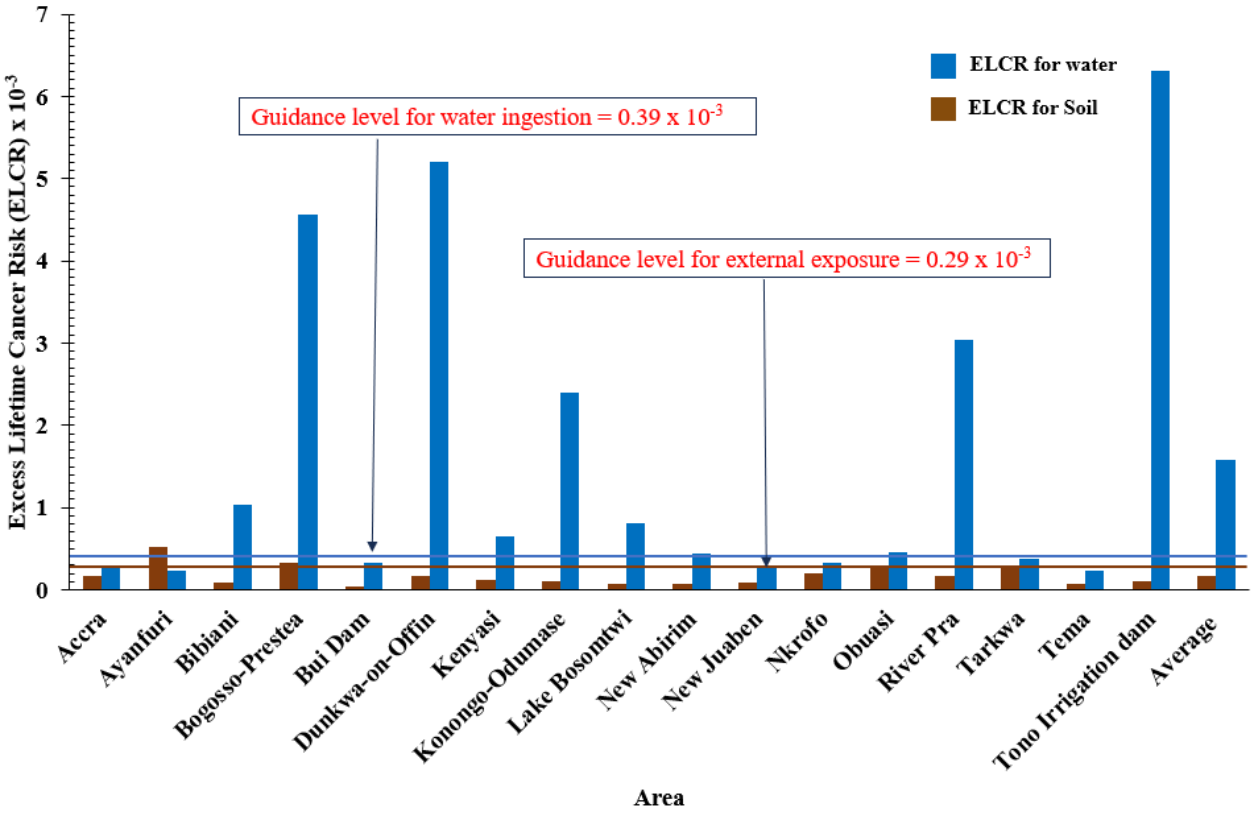

Figure 4.7. ELCR distribution for the soil and water samples across the study area.

4.5. Radiological profile of the heap pad soil for consideration as building and/or construction material.

The utilisation of NORM residue, for instance soil produced in large quantities in construction has gained significance in recent years, providing a means of reducing environmental NORM pollutants and promoting sustainability (Shahrokhi et al., 2023). The prospects of utilization as mixtures or additive materials in the construction industry could generate substantial financial advantages while reducing potential radiological consequences. The extant literature indicates that the presence of compositions or supplements of NORM residues typically results in a reduction in activity concentration the hazard indices within the raw residue (Shahrokhi et al., 2023). These hazard indices including the gamma absorbed dose rate, radium equivalent, gamma index, the external hazard index and internal hazard index are the commonly modelled indices for determining if a soil or NORM residue can be reused in construction or building materials (Shahrokhi et al., 2023). There are potential opportunities to reuse the leftover heap pad soil from

the leaching facility of the gold mine at Tarkwa as construction or building materials. Tarkwa, is a well-known major mining area which also practice heap-leaching operations and hence has generated significant quantities of leftover heap pad soils.

Table 4.8 and Table 4.9 shows the radiological profile of ^{238}U, ^{232}Th, and ^{40}K at heap pads/soil depths of 0-20 cm and 20-50 cm respectively. At depth 0-20 cm, the lowest and highest mean values of the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K obtained were 7±1 Bq/kg and 14±3 Bq/kg, 76±1 Bq/kg and 15±9 Bq/kg, and 55±1 Bq/kg and 371±55 Bq/kg respectively. Similarly, at depth 20-50 cm, the lowest and highest mean values of the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K are 7±1 Bq/kg and 14±1 Bq/kg, 180±3 Bq/kg and 19±11 Bq/kg, and 48±25 Bq/kg and 311±28 Bq/kg respectively. These values are below the reported global populated mean of 33 Bq/kg, 45 Bq/kg and 420 Bq/kg respectively for ^{238}U, ^{232}Th, and ^{40}K in soil samples and similar to the results from the mining communities in this study and other studies (Darko et al., 2010; Faanu et al., 2011, 2013a, 2013b, 2024; UNSCEAR, 2000). Considering the depth profile, the results for ^{238}U appear to be quite similar whereas of ^{232}Th, the concentrations at 0-20 cm depth emerge as greater than that at 20-50 cm depth. This phenomenon of relatively higher activity concentration of ^{232}Th in the surface of the heap pad soil is attributable to the low solubility of ^{232}Th, which is prone to adsorption onto particulate matter and exhibits minimal leaching under acidic conditions.

Table 4.8. ^{238}U, ^{232}Th, and ^{40}K radiological profile in heap pad soil samples at depth of 0-20 cm from leach facility at Tarkwa.

Sample ID	Activity Concentration, Bq/kg			D_γ (nGy/h)	Ra_{eq} (Bq/kg)	I_γ	H_{ex}	H_{in}	E_{ex} (mSv/y)
	^{238}U	^{232}Th	^{40}K						
North Heap Leach	11±4 (6-16)	33±11 (17-46)	181±37 (142-218)	33±10	72±22	0.26±0.08	0.19±0.06	0.22±0.07	0.16±0.01
North Overland Conveyors	14±3 (10-19)	55±9 (45-67)	371±55 (315-426)	55±5	121±11	0.45±0.07	0.33±0.03	0.37±0.03	0.27-0.02
Old West Pad	10±1 (9-11)	16±1 (13-18)	221±5 (217-229)	23±1	50±1	0.19±0.01	0.13±0.04	0.16±0.05	0.12±0.01
South ADR	7±1 (5-9)	19±3 (12-23)	177±9 (163-189)	22±2	48±5	0.18±0.02	0.13±0.01	0.15±0.02	0.11±0.01
South Crushing Unit	8±1 (6-10)	21±4 (14-25)	224±90 (134-312)	26±5	55±10	0.21±0.05	0.15±0.03	0.17±0.03	0.13±0.01
South Ponds	7±1 (5-10)	17±4 (12-24)	209±34 (168-264)	22±1	47±4	0.18±0.03	0.13±0.01	0.15±0.01	0.11±0.01
West Pad and Ext.	13±1 (11-15)	35±6 (21-43)	263±10 (231-295)	38±5	83±9	0.31±0.04	0.22±0.003	0.26±0.03	0.19±0.02
Blue Ridge	13±5 (8-24)	28±5 (17-35)	216±28 (167-248)	32±5	70±12	0.26±0.05	0.19±0.03	0.22±0.04	0.16±0.01
South Heap Pad	10±1	23±5	164±26	25±4	56±9	0.20±0.04	0.15±0.02	0.18±0.04	0.12±0.01

	(9-11)	(17-29)	(131-190)						
North Aglo Facility	15±3 (10-18)	38±14 (28-54)	249±4 (222-254)	40±10	89±23	0.32±0.08	0.24±0.06	0.28±0.07	0.20±0.01
North Pond	11±1 (9-12)	18±5 (15-22)	79±1 (57-82)	19±3	43±3	0.15±0.03	0.12±0.03	0.15±0.03	0.09±0.01
North Reagent	11±2 (8-13)	21±5 (17-29)	200±28 (154-227)	26±4	56±9	0.21±0.04	0.15±0.02	0.18±0.02	0.13±0.01
Mean	**11±2**	**27±6**	**213±27**	**30±6**	**66±3**	**0.24±0.05**	**0.18±0.02**	**0.21±0.02**	**0.15±0.01**
Mean Range	**7-15**	**14-55**	**79-371**	**19-55**	**43-121**	**0.15-0.45**	**0.12-0.33**	**0.15-0.37**	**0.09-0.27**
World Average and/ or Limits	**33**	**45**	**420**	**60**	**370**	**1**	**1**	**1**	**0.07** [a] **1** [b]

[a] public exposure limit; [b] construction limit; MDA: ^{238}U (1 Bq/kg), ^{232}Th (1 Bq/kg), ^{40}K (2 Bq/kg)

Table 4.9. ^{238}U, ^{232}Th, and ^{40}K radiological profile in heap pad soil samples at depth of 20-50 cm from leach facility at Tarkwa.

Sample ID	Activity Concentration, Bq/kg			D_γ (nGy/h)	Ra_{eq} (Bq/kg)	I_γ	H_{ex}	H_{in}	E_{ex} (mSv/y)
	^{238}U	^{232}Th	^{40}K						
North Heap Leach	10±1 (8-12)	23±2 (20-27)	218±8 (205-230)	28±2	60±3	0.22±0.02	0.16±0.01	0.19±0.01	0.14±0.01
North Overland Conveyors	15±1 (13-17)	48±11 (7-61)	311±28 (256-341)	49±7	108±17	0.39±0.07	0.29±0.05	0.33±0.05	0.24±0.02
Old West Pad	13±1 (12-4)	27±5 (17-31)	220±3 (216-222)	31±3	69±8	0.25±0.03	0.19±0.02	0.22±0.02	0.15±0.01
South ADR	7±1 (5- 9)	22±4 (15- 26)	252±15 (245-263)	27±2	58±6	0.22±0.03	0.16±0.01	0.18±0.02	0.13±0.01
South Crushing Unit	8±1 (6-10)	25±5 (16-30)	246±23 (222-269)	29±3	63±7	0.23±0.04	0.17±0.02	0.19±0.02	0.14±0.01
South Ponds	7±1 (5-10)	17±4 (12- 24)	180±25 (110-221)	21±3	45±7	0.17±0.03	0.12±0.02	0.14±0.02	0.10±0.01
West Pad and Ext.	12±1 (10-14)	31±8 (19-43)	272±30 (235-320)	36±5	77±13	0.29±0.05	0.21±0.03	0.24±0.03	0.18±0.01
Blue Ridge	10±2 (7-14)	28±5 (19-36)	213±13 (195-233)	30±4	66±8	0.24±0.04	0.18±0.02	0.21±0.02	0.15±0.01
South Heap Pad	9±1	17±3	224±9	24±3	51±6	0.19±0.02	0.14±0.02	0.16±0.02	0.12±0.01

	(7-11)	(11-21)	(212-240)						
North Aglo Facility	14±3 (10-19)	45±9 (20- 54)	238±14 (244 -255)	44±7	97±15	0.35±0.06	0.26±0.04	0.30±0.05	0.21±0.02
North Pond	19±1 (18-20)	35±9 (29-42)	199±2 (198-205)	38±5	84±12	0.30±0.05	0.23±0.03	0.28±0.03	0.19±0.01
North Reagent	12±4 (9-18)	25±3 (20-27)	259±30 (223-297)	31±3	68±6	0.25±0.04	0.18±0.02	0.22±0.02	0.15±0.01
Mean	**11±2**	**29±6**	**236±17**	**32±5**	**70±11**	**0.26±0.04**	**0.19±0.03**	**0.22±0.03**	**0.16±0.01**
Mean Range	**7-19**	**14-48**	**180-311**	**21-49**	**45-108**	**0.17-0.39**	**0.12-0.29**	**0.14-0.33**	**0.10-0.24**
World Average and/ or Limits	**33**	**45**	**420**	**60**	**370**	**1**	**1**	**1**	**0.07** [a] **1** [b]

[a] public exposure limit; [b] construction limit; MDA: ^{238}U (1 Bq/kg), ^{232}Th (1 Bq/kg), ^{40}K (2 Bq/kg)

4.5.1. Radionuclides correlation matrix at different depths

As demonstrated in Figure 4.8, at both depths, there is a consistent high correlation between ^{238}U and ^{232}Th, demonstrating a persistent correlation between ^{238}U and ^{232}Th. Concerning the ^{238}U and ^{40}K radionuclides, the colouration is once more comparable at the two depths. However, it is observable that as the depth is increased, the colouration of these two radionuclides is reduced. It is suspected that the correlation behaviour may be attributable to the mobility and solubility of these radionuclides within the heap pad soil. The results also demonstrate that ^{232}Th and ^{40}K are moderately linked across both depths, indicating a steady yet unassuming correlation among the two radionuclides. This phenomenon can be further elucidated by the analogous interactions of ^{232}Th and ^{40}K within environmental factors and soil components.

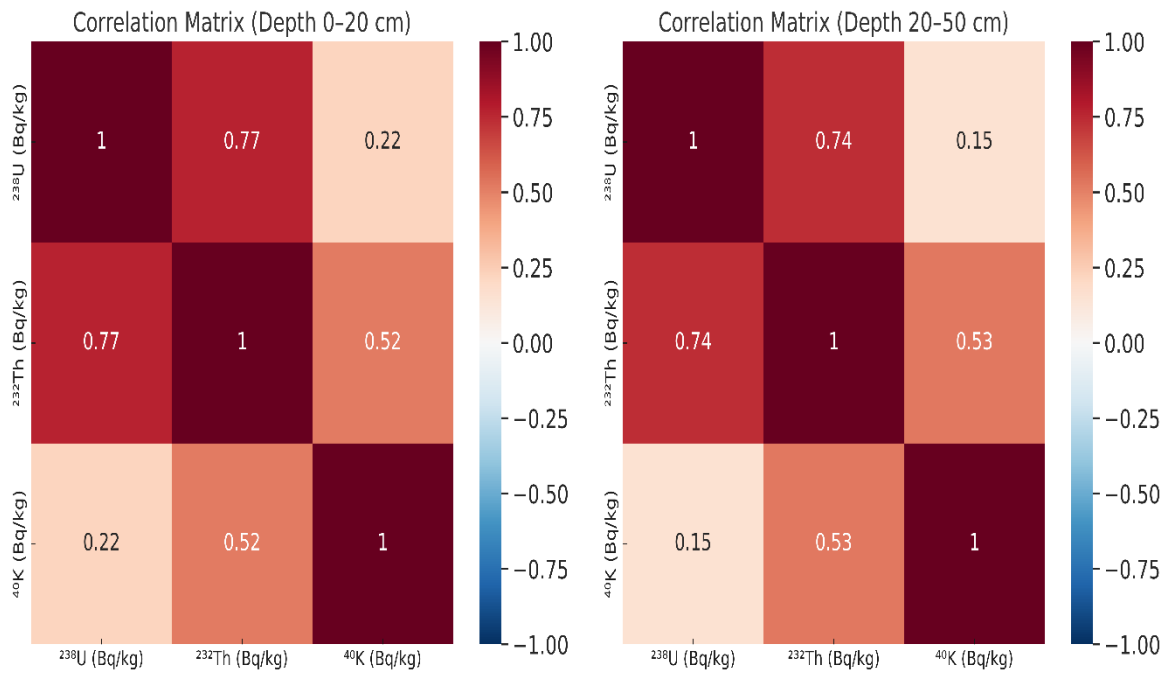

Figure 4.8. Correlation matrix between radionuclides at different depths.

The T-tests were used to compare the average concentrations of individual radionuclide at the different depths, and the results suggests there is no observable statistically significant differences among the radionuclides irrespective of the depth (all p-values > 0.05). As illustrated in Figure 4.9 and Figure 4.10, the three-dimensional scatter plots demonstrate the distribution of radionuclide concentrations at both depths.

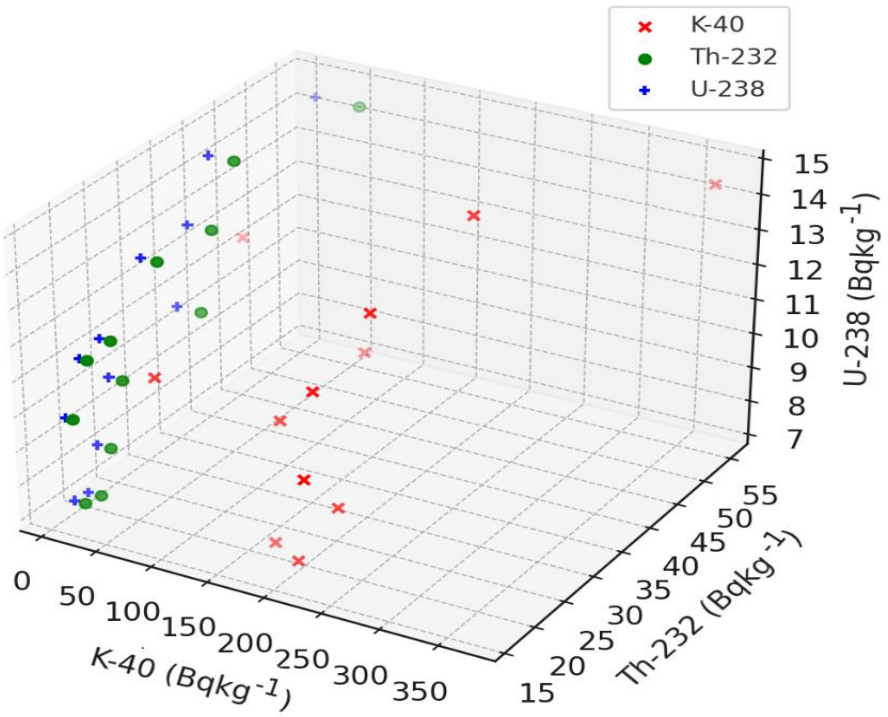

Figure 4.9. Three-dimensional scatter plot of ^{238}U, ^{232}Th, and ^{40}K concentration of heap pad soil samples taken from depth 0-20 cm.

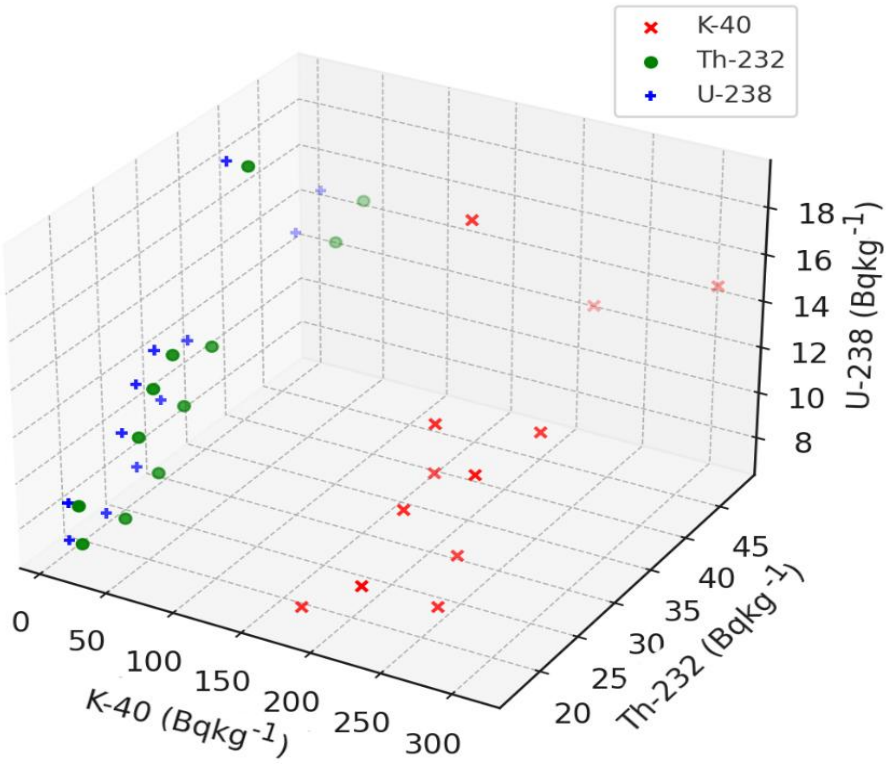

Figure 4.10. Three-dimensional scatter plot of ^{238}U, ^{232}Th, and ^{40}K concentration of heap pad soil samples taken from depth 20-50 cm.

4.5.2. Radiological profile of the heap pad soil and the feasibility of its integration into building and construction materials.

As show in Table 4.8 and Table 4.9, the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K determined in the heap pad soils of the Tarkwa leach facility reflect a generally low radiological profile relative to international reference levels soils and NORM residues reused in construction. The mean activity concentrations for the 0–20 cm layer were 11 Bq/kg, 27 Bq/kg, and 213 Bq/kg for ^{238}U, ^{232}Th, and ^{40}K, respectively, while those at 20–50 cm depth were equally comparable at 11 Bq/kg, 29 Bq/kg, and 236 Bq/kg for ^{238}U, ^{232}Th and ^{40}K respectively. These values are below the worldwide averages of 33 Bq/kg, 45 Bq/kg, and 420 Bq/kg and the IAEA exemption levels of 1000 Bq/kg for ^{238}U and ^{232}Th, and 10,000 Bq/kg for ^{40}K, which warrant regulatory control (UNSCEAR, 2000).

Additionally, as show in Table 4.10, the results from the heap pad soils are substantially lower than concentrations typically observed in industrial residues such as red mud, fly ash, or phosphogypsum reported in previous studies from other countries including Ghana, ranges from 3.1 Bq/kg to 265 Bq/kg for ^{238}U or ^{226}Ra, 2.3 Bq/kg to 321.3 Bq/kg for ^{232}Th, and 18 Bq/kg to 4952 Bq/kg for ^{40}K. According to literature, the activities of ^{238}U and ^{226}Ra are largely in equilibrium with each other. Accordingly, the mean absorbed dose rates in the heap pad soils (30–32 nGy/h) are well below the UNSCEAR screening value of 60 nGy/h and contrast sharply with the elevated dose rates (11.8 nGy/h $\geq$ absorbed dose rates $\leq$ 293.7 nGy/h) calculated for various NORM residues such as shown in Table 4.10. In a similar manner, the calculated gamma indices (0.24–0.26), external hazard index (0.18-0.19), internal hazard index (0.21-0.22) and annual effective dose (0.15-0.16 mSv/y) for the Tarkwa heap pad soils are considerably below the EU Basic Safety Standards (EU-BSS) reference value of 1, corresponding to 1 mSv/y for indoor exposure (Buranurak and Pangza, 2018; EC, 1999). Even the most active local zone, the North Overland Conveyor area, exhibited higher activity and radiological hazard indices in comparison with the other areas, they remained within acceptable levels for unrestricted reuse.

Table 4.10. Radiological properties of NORM residues in some selected countries.

Country	NORM Residue	Activity Concentration (Bq/kg)			H_{ex}	H_{in}	I_γ	D_γ (nGy/h)	E_{ex} (mSv/y)	Reference
		^{238}U or ^{226}Ra	^{232}Th	^{40}K						
Slovenia and Serbia	Limestone	41.2	41.8	568.0	0.41	0.50	0.54	129.00	0.63	Fidanchevski et al., 2022
		3.1	2.3	18.0	0.04	0.03	0.02	13.20	0.65	
Tanzania		15.5	6.6	38.6	0.32	0.12	0.09	24.60	0.12	Amasi et al., 2014
Türkiye		3.5	9.3	484.0	0.14	0.15	0.22	52.17	0.25	Baykara et al., 2011
Spain	Phosphogypsum	237.2	71.8	538.8	1.03	1.67	1.30	175.42	0.86	Contreras et al., 2018
Türkiye		12.5	2.7	1141.9	0.20	0.30	0.44	105.82	0.51	Baykara et al., 2011
Tanzania		6.2	3.7	43.7	0.04	0.06	0.05	11.80	0.06	Amasi et al., 2014
Egypt		92.0	42.0	499.3	0.37	0.47	0.68	89.56	0.50	Hassan et al, 2014
		31.7	55.0	116.0	0.32	0.41	0.42	52.70	0.26	Abbady et al., 2005
Slovenia and Serbia	Pb-Zn mine by-product	34.0	15.0	345.0	0.27	0.31	0.30	86.40	0.42	Fidanchevski et al., 2022
Serbia	Granite	129.0	92.0	1045.0	0.92	1.27	1.24	38.00	0.19	Todorovic et al., 2017
Tanzania	Clay	42.9	31.2	107.8	0.40	0.53	0.52	123.00	0.61	Amasi et al., 2014
Hungary	Red Mud	265.0	264.0	283.0	1.79	2.51	2.30	293.69	1.44	Kovacs et al., 2013
		180.0	264.0	283.0	1.56	2.05	2.01	254.42	1.25	

Spain		100.5	321.3	55.1	1.52	1.80	1.79	242.79	1.19	Alonso et al., 2018
	Fly ash	88.4	85.1	868.0	0.75	0.99	0.97	128.44	0.63	Alonso et al., 2018
Vietnam		77.4	91.7	956.2	0.76	0.97	1.04	131.02	0.64	Vu et al., 2021
India		118.6	147.3	352.0	1.03	1.28	1.25	158.40	0.78	Gupta et al., 2013
Spain	Blast furnace Slag	96.7	30.0	96.1	0.40	0.66	0.51	66.80	0.33	Alonso et al., 2018
Tanzania	Pozzolans	64.2	111.8	611.4	0.74	0.92	0.98	231.00	1.13	Amasi et al., 2014
Türkiye	marble	72.0	11.9	1218.2	0.49	0.69	0.71	22.00	0.11	Baykara et al., 2011
Tanzania	Sandstone	13.0	21.6	340.7	0.19	0.23	0.27	62.90	0.31	Amasi et al., 2014
Türkiye		24.8	18.0	1158.3	0.30	0.44	0.56	71.27	0.34	Baykara et al., 2011
Vietnam	Stone	57.2	51.5	820.6	0.52	0.68	0.72	91.75	0.45	Vu et al., 2021
Türkiye	Sand	9.2	8.4	1298.2	0.32	0.35	0.51	63.60	0.31	Baykara et al., 2011
Vietnam		46.7	49.9	607.0	0.45	0.57	0.61	77.03	0.38	Vu et al., 2021
Ghana		14.3	15.4	115.6	0.09	0.20	0.23	12.60	0.13	Otoo et al., 2018
Mean		**69.3**	**68.9**	**698.0**	**0.61**	**0.78**	**0.81**	**111.62**	**0.61**	
Range		**3.1-265.0**	**2.3-321.3**	**18.0-4952.0**	**0.04-1.79**	**0.03-2.15**	**0.02-2.30**	**11.80-293.69**	**0.06-1.44**	

^{238}U and ^{226}Ra are taken as proxy based on secular equilibrium

Table 4.11. Radiological properties of building/or construction materials in some selected countries.

Country	Construction/Building Material	Activity Concentration (Bq/kg)			H_{ex}	H_{in}	I_γ	D_γ (nGy/h)	E_{ex} (mSv/y)	Reference
		$^{238}U/^{226}Ra$	^{232}Th	^{40}K						
Israel	Concrete	33.5	9.2	63.6	0.14	0.23	0.12	23.69	0.12	Kovler, 2017
	Concrete Mixtures	31.9	9.0	66.1	0.13	0.22	0.17	22.93	0.11	
	fly ash Concrete	32.7	9.4	66.0	0.14	0.23	0.12	23.54	0.12	
Serbia		26.4	22.5	243.6	0.21	0.28	0.29	35.94	0.18	Ignjatovic et al., 2017
Hungary	Manganese clay (Red Mud) bricks	52.0	40.0	607.0	0.42	0.56	0.58	73.50	0.36	Kovacs et al., 2017
Türkiye	Bricks	15.7	3.8	201.4	0.03	0.14	0.14	34.70	0.02	Baykara et al., 2011
Albania		33.4	42.2	644.1	0.39	0.48	0.54	67.97	0.54	Xhixha et al., 2013
Spain	Portland Cement	15.8	16.8	262.0	0.16	0.20	0.23	28.37	0.14	Alonso et al., 2018
Thailand		25.7	16.7	140.5	0.16	0.23	0.22	27.81	0.14	Buranurak, and Pangza, 2018
Vietnam	Cement	40.1	27.4	253.3	0.27	0.38	0.36	45.64	0.22	Vu et al., 2021
Tanzania		46.3	28.5	227.8	0.29	0.40	0.37	91.90	0.45	Amasi et al., 2014
Türkiye		24.7	20.7	2493.1	0.66	0.73	1.02	245.17	1.20	Baykara et al., 2011
Ghana		35.9	25.4	233.0	0.25	0.34	0.32	41.60	0.21	Kpeglo et al., 2011

	32.6	13.4	146.3	0.07	0.26	0.18	15.20	0.08	Otoo et al., 2018
Mean	**31.5**	**20.5**	**439.0**	**0.25**	**0.34**	**0.35**	**60.10**	**0.30**	
Range	**15.7-52.0**	**3.8-42.2**	**63.6-2493.1**	**0.03-0.66**	**0.14-0.70**	**0.12-1.02**	**22.93-245.17**	**0.02-1.20**	

^{238}U and ^{226}Ra are taken as proxy based on secular equilibrium

When the radiological properties such as the gamma index, the external hazard index, the internal hazard index and indoor annual effective dose of the heap pad soils were evaluated against the radiological properties of processed building materials with gamma index (0.12-1.02), external hazard index (0.03-0.66), internal hazard index (0.14-0.70), and indoor annual effective does (0.02-1.20 mSv/y) from other studies from in various countries including Ghana as show in Table 4.11, the heap pad soil demonstrates remarkably comparable or reduced radiological properties. Consequently, the Tarkwa heap soils demonstrate a greater degree of radiological alignment with conventional aggregates than with high-activity industrial residues, thereby supporting their potential reuse as a partial aggregate or additive in cementitious composites, provided that geochemical compatibility and mechanical strength parameters are met.

A comparison with the NORM reduction methods as shown in Table 4.12, further reinforces the applicability of the heap pad soil in building and/or construction materials. The mixture or dilution strategies such as blending NORM-rich residues with inert binders or employing alkali activation techniques are conceptually analogous to the potential valorisation of heap pad soils in concrete or brick matrices (Krivenko et al., 2017; Nuccetelli et al., 2017). The relatively low gamma indices (≤ 0.26) of the Tarkwa material indicate that even direct incorporation, without advanced fixation or firing, would remain below the 1 mSv/y dose constraint, satisfying the EU-BSS and IAEA safety thresholds (EU, 1999; IAEA, 2014a).

Table 4.12. NORM residue reduction methods.

NORM residue	Applicable reduction Method	Reference
Gypsum or Phosphogypsum	Sulphur polymer metrics with cement	Garcia-Diaz et al., 2013, 2016
	Binding with zeolite	Nizeviciene et al., 2018; Vaiciukyniene et at., 2018
	Valorisation for cement or Building material production	Garcia-Diaz et al., 2016; Fidanchevski et al., 2022
Bottom ash	Binding with zeolite	Nizeviciene et al., 2018; Vaiciukyniene el at., 2018

	Proportionate or reducing composite with cement	Alonso et al., 2018; Croymans et al., 2017; Ignjatovic et al., 2017; Leonardi et al., 2018; Puertas et al 2021, 2015, Vu et al., 2021
	Proportionate with Woodchip ashes	Adach and Izmer 2018; Liu et al., 2017
Clay	Firing method	Contreras et al., 2018; Kovacs et al., 2017
Fly ash	Proportionate or reducing composite with cement	Alonso et al., 2018; Croymans et al., 2017; Ignjatovic et al., 2017; Leonardi et al., 2018; Puertas et al 2021, 2015, Vu et al., 2021
	Proportionate with Woodchip ashes.	Adach and Izmer 2018; Liu et al., 2017
	Alkali activation concrete	Krivenko et al., 2017; Nuccetelli et al., 2017
Blast furnace slag	Proportionate or reducing composite with cement	Alonso et al., 2018; Croymans et al., 2017; Ignjatovic et al., 2017; Leonardi et al., 2018; Puertas et al 2021, 2015, Vu et al., 2021
Red mud or bauxite quarry waste	Valorisation for cement or Building material production.	Fidanchevski et al., 2022; Garcia-Diaz et al., 2016; Hegedűs et al., 2016
	Alkali activation concrete	Krivenko et al., 2017; Nuccetelli et al., 2017
Limestone	Valorisation for cement or Building material production	Fidanchevski et al., 2022; Garcia-Diaz et al., 2016
ilmenite mud	Valorisation for cement or Building material production	Fidanchevski et al., 2022; Garcia-Diaz et al., 2016

From a sustainability perspective, reutilizing such low-activity heap soils represents a dual advantage; first, environmental protection through residue volume reduction, and second, resource efficiency by substituting virgin raw materials. Shahrokhi et al. (2023), emphasised that radiological sustainability requires balancing dose optimization with circular-economy benefits. In this context, the Tarkwa residue, with its average $H_{ex} \approx 0.19$ and $H_{in} \approx 0.22$, provides a rare example of a naturally attenuated NORM residue requiring minimal treatment before reuse. Unlike red mud or phosphogypsum, where the radiological properties often exceed the recommended levels, necessitating immobilisation or encapsulation, the Ghanaian heap pad soil falls well below recommended levels (Contreras et al., 2018; Schroeyers et al., 2018). Furthermore, the depth-wise similarity between the 0–20 cm and 20–50 cm layers indicate limited vertical migration of radionuclides, suggesting radiological stability and uniformity, which are advantageous for homogenised mixing in building composites. The higher surface ^{232}Th activity supports the known low solubility and surface adsorption of thorium (Darko et al., 2010; Faanu et al., 2013), implying minimal leaching risk under alkaline cementitious conditions.

In summary, a comparison of the radiological properties of the heap pad soil with international NORM residue inventories (Table 4.8, Table 4.9, Table 4.10, and Table 4.11) reveals that the activity concentrations of Tarkwa materials are significantly lower than those of typical industrial by-products under consideration for reuse as shown in Figure 4.11. As clearly shown in Figure 4.11, the relatively low activity concentrations in the heap pad soils compared with typical NORM residues and standard building materials, emphasizing their radiological safety and potential reuse in sustainable construction. Additionally, the derived hazard indices and annual effective doses (≤ 0.04 mSv/y) are well within the public exposure limits (UNSCEAR, 2000), thus suggest that the mine's heap pads soils are radiologically safe and sustainable material suitable for partial incorporation into building and/or construction materials such as bricks, blocks, sub-base layers, low-grade concrete products, or for road constructions. With appropriate physio-mechanical assessment and blending optimization, this reuse could simultaneously advance Ghana's waste-minimization and circular-economy objectives in the mining sector while remaining fully compliant with radiological safety standards.

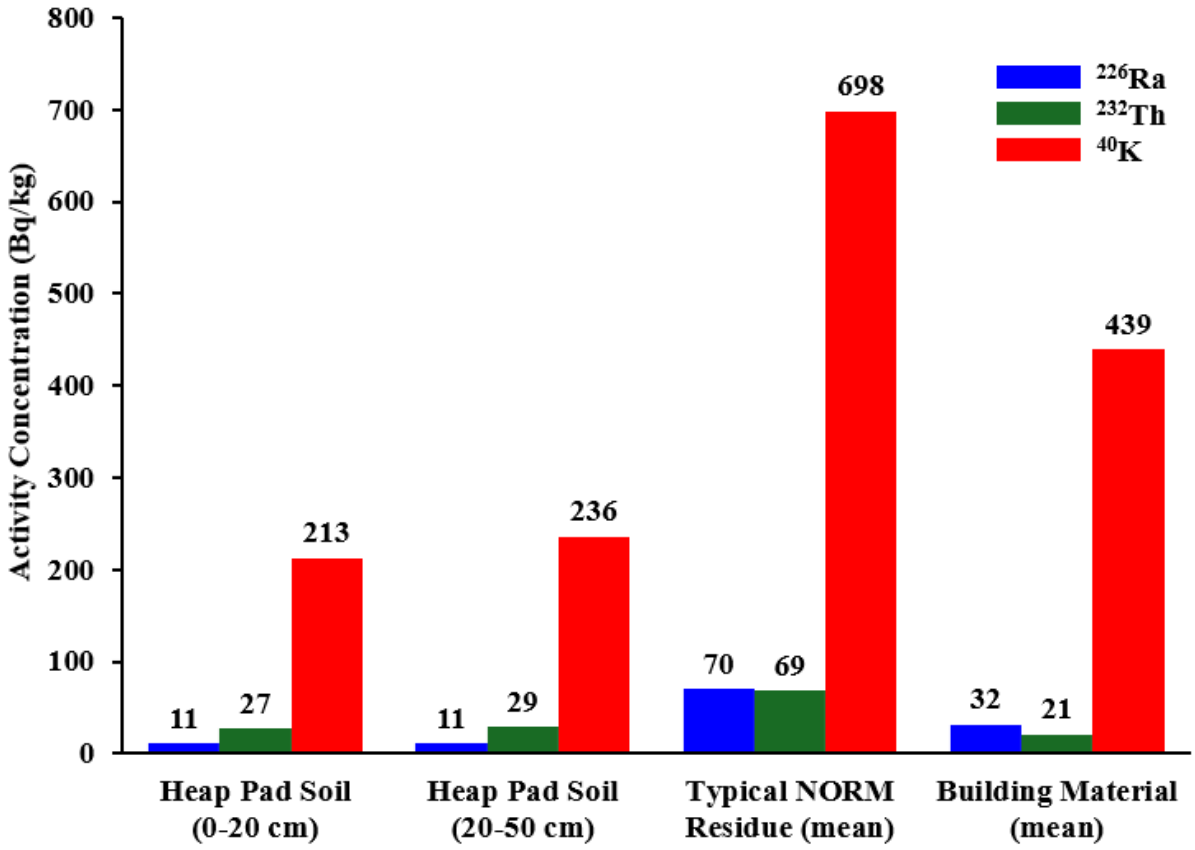

Figure 4.11. A comparative activity concentration of the heap pad soil to NORM residue and Building materials

4.6. Natural radiological profile of ^{226}Ra, ^{232}Th, and ^{40}K in the sampled rice

Table 4.13 presents the natural radiological profile of ^{226}Ra, ^{232}Th, and ^{40}K in the rice samples under study. The average activity concentration of ^{226}Ra ranges from 0.50 Bq/kg to 10.60 Bq/kg with total mean of 5.03 Bq/kg; ^{232}Th average activity ranges from 0.68 Bq/kg (with about 4 individual towns below the minimum detectable activity (MDA)) to 3.80 Bq/kg with total mean of 1.76 Bq/kg; and ^{40}K ranges from 16.63 Bq/kg (with 1 town below MDA) to 63.88 Bq/kg with mean value of 39.10 Bq/kg. However, the higher concentration of ^{226}Ra observed for Town 5, Town 8 and Town 9, suggests localised enhancements, potentially attributable to underlying geological formations in addition to unregulated mining activities. Conversely, Town 3 and Town 4 exhibited the lowest levels of ^{226}Ra (<1 Bq/kg) and unappreciable concentrations of ^{232}Th.

Table 4.13. Natural radionuclide profile of rice from the various towns in the district.

Sample Town	Radionuclide concentration (Bq/kg)			E_r (mSv/y)	ELCR x10^{-3}
	^{226}Ra	^{232}Th	^{40}K		
Town1	1.88 (1.70-2.00)	0.69 (<MDA-0.75)	37.80 (36.10-38.60)	0.036	0.126
Town2	2.10 (2.00-2.20)	0.71 (0.68-0.79)	44.65 (43.20-46.10)	0.041	0.142
Town3	0.73 (0.60-0.80)	0.68 (<MDA-0.71)	16.63 (17.10-17.30)	0.016	0.055
Town 4	0.50 (0.49-0.52)	0.68 (<MDA-0.69)	30.13 (28.30-31.50)	0.017	0.058
Town 5	6.90 (2.50-12.4)	2.04 (<MDA-1.81)	63.88 (43.80-84.40)	0.126	0.441
Town 6	1.63 (1.50-1.70)	3.13 (3.00-3.20)	47.08 (45.90-48.60)	0.066	0.231
Town 7	7.83 (7.70-7.90)	1.12 (0.98-1.17)	49.64 (9.20-50.00)	0.114	0.400
Town 8	8.63 (8.20-9.40)	2.88 (2.70-3.10)	43.75 (41.70-47.60)	0.151	0.528
Town 9	9.50 (9.00-10.10)	3.80 (2.98-4.41)	37.30 (35.60-39.70)	0.134	0.469
Town 10	10.60 (10.10-11.10)	1.83 (0.91-2.10)	20.13 (MDA-30.67)	0.141	0.493
Mean	**5.03±1.75**	**1.76±0.57**	**39.10±10.12**	**0.081±0.001**	**0.291±0.001**
Mean range	**(0.50-10.60)**	**(0.68-3.80)**	**(16.63-63.88)**	**(0.016-0.151)**	**(0.055-0.528)**
MDA: ^{226}Ra (0.45 Bq/kg), ^{232}Th (0.48 Bq/kg), ^{40}K (0.55 Bq/kg)					

Notably, approximately four towns demonstrated ^{232}Th activity concentrations below the minimum detectable activity (MDA). The observed phenomenon may be attributable to one or more of the following factors: firstly, low, and appreciable ^{232}Th activity concentration; secondly, root uptake from the soil; or thirdly, relatively low activity of the same radionuclide in the soils or from water sources used for irrigation. The mean concentration of ^{226}Ra (5.03 Bq/kg) significantly exceeded the globally accepted average of 0.13 Bq/kg (UNSCEAR 2000).

In a similar vein, the presence of ^{232}Th was detected in certain towns, with levels reaching up to 3.80 Bq/kg, which exceeds the global average of 0.11 Bq/kg (UNSCEAR, 2000). These elevated values are consistent with earlier reports on rice from mineral-rich regions of Ghana and may be attributed to the geographical setting of Akyemansa, which is dominated by Birimian and granitic rocks known to be hosts for uranium and thorium-bearing minerals (Awudu et al., 2012; Dickson-Agudey et al., 2026; Faanu et al., 2016a, 2016b). Furthermore, anthropogenic activities such as illegal artisanal mining in the district are likely to enhance the bioavailability of radionuclides by disturbing soil layers and increasing environmental mobility (Faanu et al., 2024; Tettey-Larbi et al., 2013a, 2013b).

Conversely, the mean concentration of ^{40}K (39.10 Bq/kg) was found to be significantly lower than the global average of 68.5 Bq/kg, as well as the findings from other regions. The analysis of five samples from Town 10 revealed activity concentrations of ^{40}K that were below the minimum detectable activity. This might be due to potassium deficiency in the soil. This deficiency could be attributed to prolonged periods of monoculture farming without inter-fallow periods, or to variations in fertiliser application across different farms in Akyemansa. Comparable low levels have been recorded in some rice varieties from Bangladesh and Iran (Hossain et al., 2024; Hosseini et al., 2006).

The activity concentrations of natural radionuclides in rice samples from Akyemansa District also demonstrate certain similarities and slight variations when compared with other studies conducted outside the region and from other countries, as shown in Table 4.14. The observations are consistent with the findings from other mining-impacted regions in Nigeria and Malaysia, where higher concentrations of ^{226}Ra and ^{232}Th have also been reported (Okeme et al., 2016; Saeed et al., 2011). Whilst certain radionuclide activity concentration ranges overlap with others (e.g. certain results from Bangladesh, India, Iran, Nigeria, Saudi Arabia and Kuwait), certain others fall well below the reported ranges in these countries (e.g. Malaysia and even previous studies conducted in Ghana in a region with presumed non-elevated natural radionuclides). However, these variations from different countries across the world could be attributed to several factors, including variations in soil geochemistry, agricultural practices, the types and number of fertilisers used, and differences in environmental conditions (Alsaffar et al., 2016; Pulhani et al., 2015; Salman et al., 2019).

Table 4.14. Comparing radionuclide concentrations (Bq/kg) in Rice from different countries

Country	^{226}Ra	^{232}Th	^{40}K	Reference
India	0.01-0.30	0.08-0.56	45.90-86.60	Ramachandran and Mishra, 1989
Iran	0.02-0.67	0.03-0.20	7.10-111.00	Hosseini et al., 2006
	1.27-2.89	0.42-15.24	84.66-122.66	Pourimani and Anoosheh, 2015
Kuwait	0.41-0.91	0.32-0.62	32.90-101.00	Alrefae and Nageswaran, 2013
Saudi Arabia	0.10-2.60	0.10-2.30	45.00-257.20	Al-Hassan et al., 2014
Malaysia	1.50-2.80	3.60-7.50	59.90-92.20	Asaduzzaman et al., 2015
	18.33-25.10	35.49-64.97	64.80-109.93	Saeed et al., 2011
	56.97-86.13	34.71-52.14	517.05-997.59	Salih, 2018
Nigeria	0.90-2.40	0.50-2.40	78.00-111.00	Hassan et al., 2021
	5.73-13.46	5.90-13.20	35.96-87.89	Okeme et al., 2016
Bangladesh	1.00-30.10	2.80-36.00	10.60-128.80	Hossain et al., 2024
	0.47-1.66	0.04-0.49	1.09-9.23	Nahar et al., 2018
Ghana	2.61-6.92 [a]	3.61-9.50 [a]	41.70-210.80 [a]	Awudu et al., (2012)
	1.09-3.04 [b]	1.98-4.85 [b]	26.10-78.30 [b]	Dickson-Agudey et al., 2026
	0.50-10.60	0.68-3.80	16.63-63.88	[Present study]

[a] Local Rice (previous study), [b] imported (foreign) Rice

Notwithstanding the elevated levels of ^{226}Ra and ^{232}Th in certain townships, the estimated average committed effective doses in the rice samples from the study area range from 0.016 mSv/y (Town 3) to 0.151 mSv/y (Town 8), with a mean of 0.081 mSv/y (see Table 4.13). These figures are well below the 0.3 mSv/y public dose limit for ingestion set by the ICRP, and UNSCEAR and are comparable with those of other studies (Ademola and Onyema, 2014; Pourimani et al., 2015). The highest recorded effective dose was observed in Town 8 (0.151 mSv/year), although this represented only 15.1% of the threshold. These values are translated to an ELCR value between 0.055×10^{-3} and 0.528×10^{-3} at a mean value of 0.291×10^{-3} (see Table 4.13). These values are significantly lower than the global average of 1.16×10^{-3}. This finding indicates that the current dietary habits of the population do not pose a significant radiological risk or risk of developing cancer hence the consumption of rice from the district does not pose a significant radiological health risk to the population. The findings also emphasise the role of agricultural and environmental factors in determining radionuclide

uptake. For instance, the waterlogged conditions typical of rice paddies enhance the mobility of radium and thorium, thereby increasing plant uptake (Chiang et al., 2023). In light of the ongoing illegal mining activities, mitigation measures are recommended to mitigate the possible adverse effects in the future. These measures include soil pH adjustment, the use of potassium-rich fertilisers to reduce uptake of ^{226}Ra and ^{232}Th, and periodic radiological screening of rice (Alsaffar et al., 2016; Pulhani et al., 2015; Salman et al., 2019; Shanthi et al., 2012). Moreover, the incorporation of these findings into Ghana's food safety and radiation protection frameworks has the potential to enhance public health resilience, particularly in regions characterised by known geological anomalies or mining activity.

4.6.1. Transfer of Radionuclides from Soil and Water to Rice

Table 4. 15 shows the mean activity concentrations of natural radionuclides in soils, irrigation water, and rice with derived transfer factors (soil–rice; TFs) and concentration ratios (water–rice; CR_W) while Figure 4.12 compare the mean concentrations of naturally occurring radionuclides in soils, irrigation water, and rice. The values provided offer a direct assessment of the pathways through which radionuclides enter the food chain in artisanal and small-scale mining areas.

Table 4. 15. The mean activity concentrations of natural radionuclides in soils, irrigation water, and rice with corresponding transfer factors (soil–rice) and concentration ratios (water–rice).

Radionuclide	Soil (Bq/kg)	Water (Bq/L)	Rice (Bq/kg)	Soil → Rice TF (kg/kg)	Water → Rice CR_W (kg/L)
^{226}Ra (^{238}U≈^{226}Ra in soil)	24±3	1.15±0.21	5.03±1.75	0.21	4.37
^{232}Th (^{228}Th≈^{232}Th in water)	25±3	1.60±0.35	1.76±0.57	0.07	1.10
^{40}K	328±63	20.70±3.60	39.10±10.12	0.12	1.89

^{238}U in soil and ^{228}Th in water were taken as proxy for ^{226}Ra and ^{232}Th respectively based on secular equilibrium.

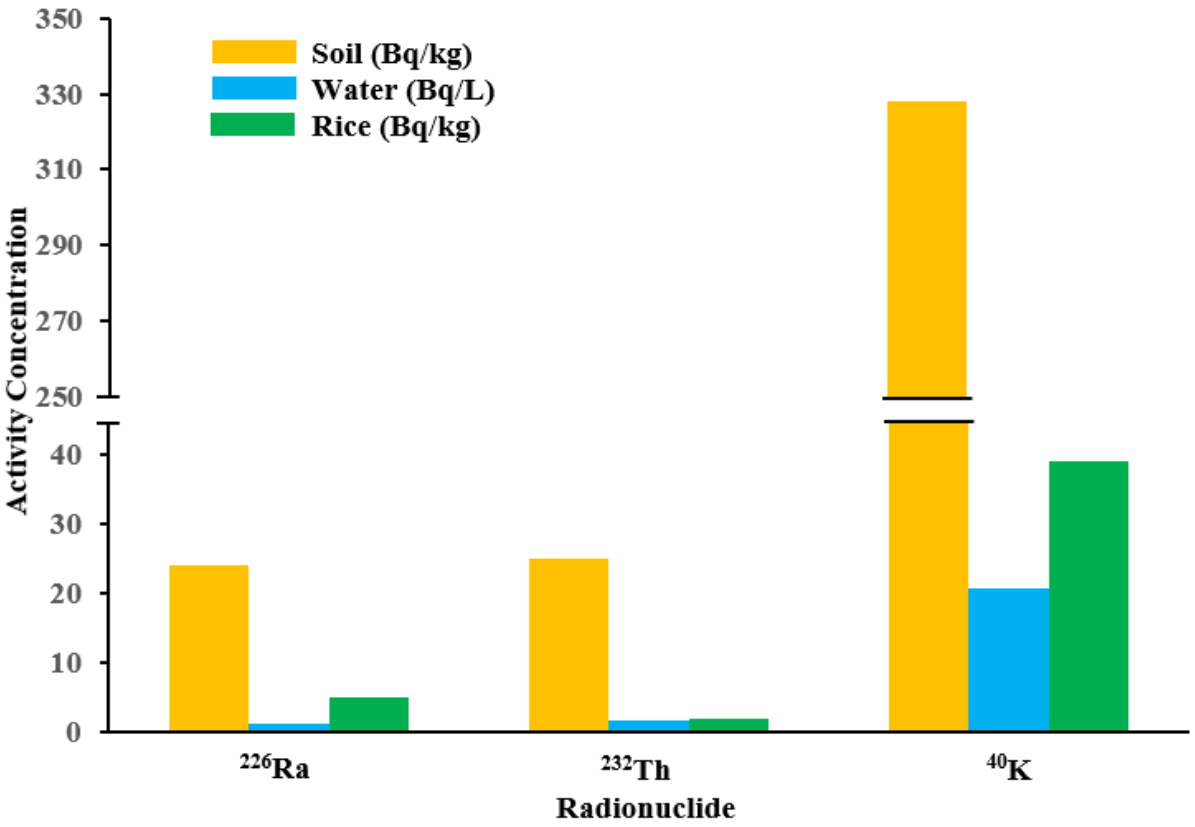

Figure 4.12. A comparison of mean activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in soil, irrigation water, and rice.

The mean activity concentration of ^{226}Ra in soil was taken as 24±3 Bq/kg (^{238}U taken as a proxy under secular equilibrium), whereas the irrigation water was found to be 1.15±0.21 Bq/L, while the mean activity level of the rice samples was found to be 5.03±1.75 Bq/kg. While the derived TF of 0.21 can be considered modest, the CR_W of 4.37 is relatively high, thus indicating that the irrigation water was a significant source of radium uptake in rice. This interpretation is reinforced by the flooded conditions that are characteristic of paddy cultivation, where soluble Ra remains available in the water column and pore water. Concurrent findings have been detailed in IAEA technical documents, which observe enhanced mobility of Ra in reducing environments and its substitution for calcium-Ca during plant uptake (IAEA, 2006). It is also established through further research in mining-impacted regions that elevated levels of Ra have been identified in rice linked to irrigation water rather than soil inventories (Shanthi et al., 2012). The present results thus confirm that ^{226}Ra transfer is dominated by pathways involving water, consistent with the observed exceedances of committed ingestion doses from water in the study area.

With a soil mean activity concentration of ^{232}Th was 25±3 Bq/kg, the irrigation water containing 1.60±0.35 Bq/L (^{228}Th taken as a proxy under secular equilibrium) and the rice sample having 1.76±0.57 Bq/kg, the calculated TF of 0.07 indicates poor soil-to-plant transfer. This is in line with the known geochemical behaviour of thorium, which is strongly adsorbed to Fe and Mn oxides, clay minerals, and organic matter. It is sparingly soluble under typical soil pH and redox conditions (IAEA, 2006; UNSCEAR, 2000). The CR_W of 1.10 indicates that in the presence of Th isotopes in the water phase, uptake into rice may occur, but at low levels relative to Ra or K. This finding supports the interpretation that ^{232}Th contributes marginally to internal doses from rice ingestion, even in areas affected by mining activities. Figure 4.13 shows a comparison of the soil-to-rice transfer factors (TF) and water-to-rice concentration ratios (CR_W) for ^{226}Ra, ^{232}Th, and ^{40}K.

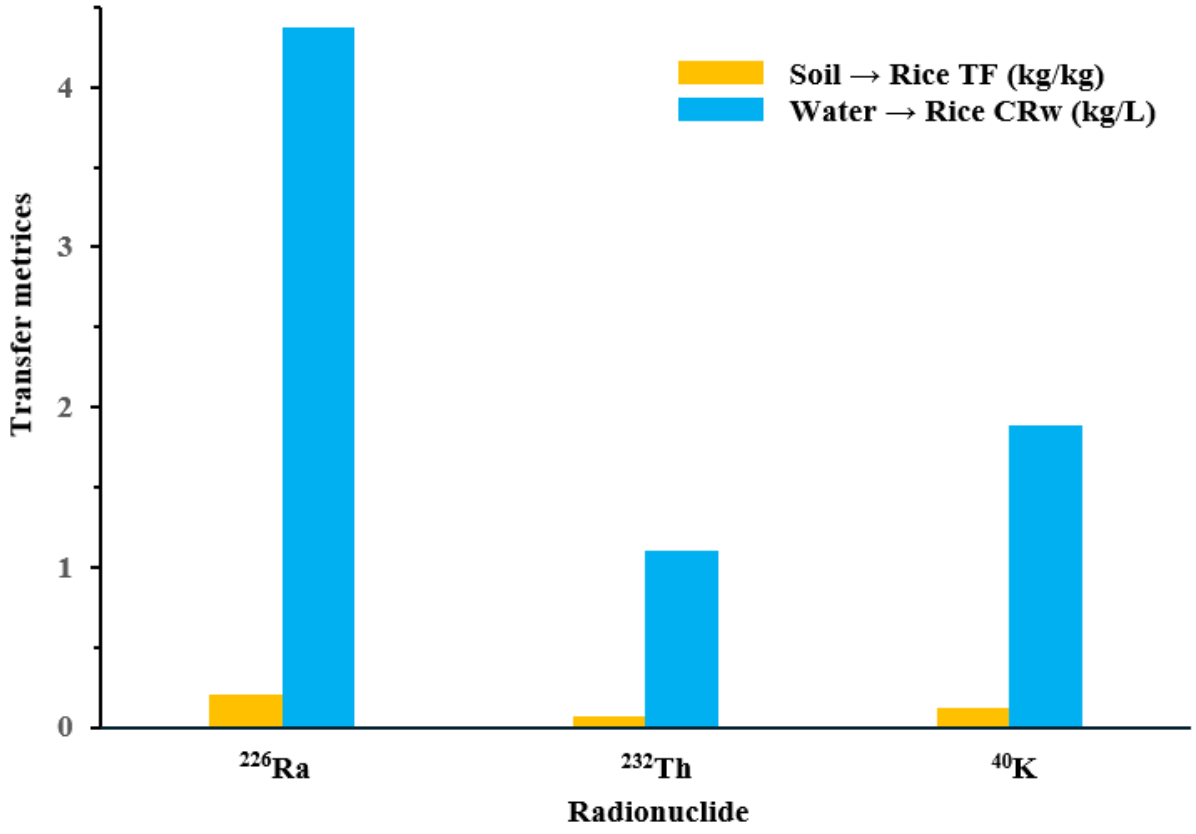

Figure 4.13. A comparison of the soil-to-rice transfer factors (TF) and water-to-rice concentration ratios (CR_W) for ^{226}Ra, ^{232}Th, and ^{40}K.

The mean soil concentration of ^{40}K was found to be 328±63 Bq/kg, in comparison to 20.70±3.60 Bq/L in irrigation water, and 39.10±10.12 Bq/kg in the rice samples, the soil-to-rice transfer factor (TF) was 0.12, indicating a strong soil-dominate uptake process. Potassium

(K) is an essential macronutrient, and its uptake is regulated by root transport systems that do not discriminate between stable K and its radioisotope ^{40}K. As evidenced by some studies, rice accumulates K primarily from soil reserves rather than irrigation water (Alsaffar et al., 2016; Pulhani et al., 2005). Despite the CR_W being 1.89 and may contribute to additional uptake, agronomic evidence suggests that exchangeable soil K pools are the dominant source for rice, especially under fertilized or K-rich conditions. This phenomenon elucidates the relatively consistent ^{40}K levels observed across the rice samples despite the variability in irrigation water concentrations.

The combined evidence from TFs and CR_W indicates contrasting pathways of radionuclide transfer into rice. ^{226}Ra exhibits a high CRw (≈4.37), confirming irrigation water as the dominant source under flooded paddy conditions, consistent with the elevated ingestion doses derived from water in the study communities. In contrast, ^{40}K shows a higher TF (≈0.12), and CR_W (≈1.89) consistent with soil-dominant and additional water uptake as potassium is an essential nutrient, reflecting its role as an essential nutrient and its ready availability from soil-water exchange sites. ^{232}Th displays both low TF (≈0.07) and CR_W (≈1.10), reflecting its poor bioavailability, limited mobility, and transfer to rice, with only minor contributions from irrigation water. These trends align with the broader interpretation that rice acts as an effective bioindicator of water-derived radium and soil-derived potassium, but not thorium. The implications for radiological risk are therefore most pronounced for Ra in irrigation water, while K uptake, though measurable, represents a natural and essential process.

SUMMARY

This study assessed the distribution of naturally occurring radionuclides ($^{238}U/^{226}Ra$, $^{232}Th/^{228}Th$, and ^{40}K) in soils, leftover heap pad soils, sludges, scales, surface waters, gross alpha and gross beta screening of boreholes and/or hand dug wells, and rice cultivated in artisanal and small-scale gold mining-affected communities in Ghana. The research was motivated by concerns over the environmental and health effects of artisanal and small-scale gold mining, which has intensified across Ghana in recent decades. While in the past years the primary health focus has been on mercury poisoning, recent scientific literature highlights that the "cocktail" of toxins such as mercury, arsenic, in addition to radioactive substances may lead to an increasing range of diseases, including kidney failure, nervous system damage, and risks of cancers. These mining activities disturb soils, contaminate water bodies, and raise the potential for radionuclide transfer into food crops. Mining plays a vital role in Ghana's economy, but the activities, especially unregulated artisanal mining have been associated with land degradation, water contamination, and food-chain transfer of contaminants. The cumulative effect of living and working in these areas are of serious health hazard. These issues raise pressing concerns for both environmental sustainability and public health. The work sought to generate baseline data, assess transfer pathways of radionuclides from soil and water into food crops, and evaluate radiological hazards associated with human exposure.

By combining high-purity germanium (HPGe) gamma spectrometry and gross alpha/beta (with PIPS detectors) screening techniques, this research provided a robust assessment of the environmental activity concentration measurements and status of selected mining communities. It also estimated the corresponding radiological hazards and risks to the public through external exposure, ingestion of contaminated water, and consumption of rice irrigated with polluted water. The results provide critical baseline data for environmental radiological assessments in Ghana and contribute to the global discourse on NORM management, radiation protection, food safety, and regulatory oversight.

The major findings of this study are presented in relation to the research objectives. The mean activity concentrations of radionuclides in soils excluding the results from the sludges and scales were 24±3 Bq/kg for ^{238}U, 25±3 Bq/kg for ^{232}Th, and 328±63 Bq/kg for ^{40}K. However, including the results of the sludges and scales, 61±16 Bq/kg (^{238}U), 49±15 Bq/kg (^{232}Th), and 296±57 Bq/kg (^{40}K) with maximum values of 87 Bq/kg, 72 Bq/kg, and 1168 Bq/kg,

respectively. These exceeded world averages reported by UNSCEAR (2000) in some cases. Radiological hazard indices were generally within safety thresholds: mean Raeq was 85±12 Bq/kg, absorbed dose rate 40±6 nGy/h, indices below 1 and annual effective dose 0.05±0.01 mSv/y, though hotspots showed higher values.

The average averaged values of ^{238}U, ^{232}Th, and ^{40}K in the leftover heap pad soils samples were determined to be 11±2 Bq/kg, 27±6 Bq/kg, and 213±27 Bq/kg respectively at 0-20 cm depth and similarly at 20-50 cm depth 11±2 Bq/kg, 29±6 Bq/kg, and 236±17 Bq/kg respectively. The corresponding absorbed dose rates were 30±6 nGy/h (at 0-20 cm depth), and 32±5 nGy/h (at 20-50 cm depth) with Ra_{eq} of 66±3 Bq/kg (at 0-20 cm depth) and 70±11 Bq/kg (at 20-50 cm depth. The hazard indices were below 1 in both cases (at 0-20 cm and 20-50 cm) with an annual effective dose of 0.15 mSv/y (at 0-20 cm depth) and 0.16 mSv/y (at 20-50 cm depth). These results were below safety limits for reuse in construction and hence could be incorporated in building and construction materials.

The surface water samples showed elevated radionuclides with mean concentrations of 1.15±0.21 Bq/L (^{226}Ra), 1.60±0.35 Bq/L (^{228}Th), and 20.70±3.60 Bq/L (^{40}K). The committed effective dose from consumption was 0.41±0.08 mSv/y (range 0.06–1.64 mSv/y), about four times the WHO guideline of 0.1 mSv/y. Excess lifetime cancer risk (ELCR) averaged 1.59×10^{-3}, exceeding the recommended threshold, with some samples as high as 6.30×10^{-3}, increasing the risk of developing cancer and hence rendering it not radiological safe to be used for domestic purposes. However, the gross alpha and gross beta screening water samples from boreholes and/or hand dug wells were all below the guidance limit of the Ghana Standard Authority (GSA) and the World Health Organisation (WHO) rendering them radiological safe to be used as drinking water and/ or for domestic purpose.

Rice samples recorded mean concentrations of 5.03±1.75 Bq/kg (^{226}Ra), 1.76±0.57 Bq/kg (^{232}Th), and 39.10±10.12 Bq/kg (^{40}K), with maxima of 10.63 Bq/kg, 3.13 Bq/kg, and 63.88 Bq/kg, respectively. The analysis of transfer metrics demonstrated distinct radionuclide uptake pathways in rice cultivated in mining-impacted areas. ^{226}Ra exhibited a high water-to-rice concentration ratio ($CR_W \approx 4.37$), confirming irrigation water as the significant pathway, whereas ^{40}K showed a higher soil-to-rice transfer factor ($TF \approx 0.12$) and possible additional uptake from the irrigation water ($CR_W \approx 1.89$), consistent with uptake of potassium from soil and water as an essential nutrient. By contrast, ^{232}Th displayed both low TF (≈0.07) and CR_W (≈1.10), reflecting minimal bioavailability, suggesting that rice acts as a bioindicator of radium

from water and potassium from soil, but not of thorium. These results compare well with other studies from other countries.

Dose assessments and health risks: The annual effective dose from soils was 0.05±0.01 mSv/y, averagely 0.035 mSv/y for the heap pad soils, while water ingestion contributed 0.41 mSv/y on average. Rice ingestion added further but lower contributions. Although total doses generally remained below the ICRP (2007) limit of 1 mSv/y, ELCR values from water ingestion surpassed the safety criterion, indicating water and rice as the most critical exposure pathways.

The findings of this study indicated that unregulated artisanal and small-scale mining in Ghana leads to an augmentation in the levels of naturally occurring radionuclides in soils, water, and rice. This phenomenon has been demonstrated to engender a range of implications for radiological risk. Soil samples exhibited elevated radionuclide levels in comparison to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) global averages. However, hazard indices such as the radiological equivalent level (Raeq), gamma index, external hazard index, and internal hazard index, along with the annual effective dose, predominantly remained within international safety thresholds. These findings imply that soil alone does not represent the most pressing concern; however, hotspots do necessitate monitoring. Water sources presented greater risks, with mean committed effective doses (0.41 mSv/y) exceeding WHO guidelines and ELCR values above permissible thresholds, indicating long-term health concerns for communities relying on such water. Rice samples confirmed the transfer of radionuclides from soil and water into the food chain, particularly for ^{40}K and ^{226}Ra. Although the ingestion of rice did not exceed recommended limits when ingested in isolation, it did contribute significantly to the overall exposure when combined with water and soil exposure. It is evident that, whilst most total doses remain below the 1 mSv/y ICRP public limit, the exceedances in water and the cumulative exposure risks highlight the urgent need for intervention. The study therefore provides critical baseline data that underscores the environmental and public health implications of artisanal mining in Ghana.

Some recommendations on the implication of the results and research studies should include Policy and Regulation; it is imperative that the enforcement of environmental and radiological safety regulations governing artisanal and small-scale mining is strengthened. The development of national guidelines for NORM monitoring in soils, water, and crops is imperative, as is the integration of radiological assessments into mining permits and

environmental impact assessments. It is important also to conduct routine monitoring of surface and groundwater for gross alpha and beta activities which is a relatively cost-effective screening method to ensure water safety. In circumstances where concentrations of contaminants exceed the limits stipulated by the World Health Organisation (WHO) or the Global Standards Association (GSA), further specific isotopic analysis should be conducted while sorting for or establishing alternative sources of potable water for affected communities. The implementation of remediation strategies, may include but not limited to engineered barriers, tailing management, and phytoremediation, is imperative for the management of contaminated sites. On Food Safety and Agriculture, it is recommended that regular radionuclide screening of rice and other staple food crops be implemented in areas that have been impacted by mining activities. It is urgent that farmers receive comprehensive training on the optimal application of irrigation systems and the judicious use of fertilisers to ensure environmental sustainability and economic efficiency. It is imperative to raise public awareness regarding the potential food safety risks associated with mining pollution. Finally, in terms of further future Research, Data Development, Capacity Building and Collaboration, it is suggested that longitudinal studies are conducted to track seasonal and long-term variability in radionuclide dispersion. The expansion of research into other food crops, alongside the development of Ghana-specific transfer factor models for accurate predictions, is recommended. Additionally, it is necessary that local scientists, regulators, and community monitors are trained in radiological assessment. Collaborations with institutions such as the Department of Radiochemistry and Radioecology, Faculty of Engineering of the University of Pannonia and international bodies such as the International Atomic Energy Agency (IAEA) are encouraged to facilitate the establishment of optimal practices and assessment in the field of NORM management. It is recommended that community-based monitoring be encouraged to facilitate the involvement of local stakeholders in the protection of environmental health.

THESIS POINTS

I. Thesis

I investigated the distribution of naturally occurring radionuclides of ^{238}U, ^{232}Th, and ^{40}K in soils, within artisanal and small-scale mining affected communities in Ghana. I found mean activity concentrations in soils of 24±3 Bq/kg (^{238}U), 25±3 Bq/kg (^{232}Th), and 328±63 Bq/kg (^{40}K), with maximum values of 87, 72, and 1168 Bq/kg, respectively. The calculated Ra_{eq} of 85±12 Bq/kg; absorbed dose rate of 40±6 nGy/h; indices below 1 and annual effective dose 0.05±0.01 mSv/y generally remained below international safety thresholds, with some localized hotspots exceeding UNSCEAR (2000) world averages and of low-risk radiological concern.

II. Thesis

I investigated the distribution of naturally occurring radionuclides of ^{238}U, ^{232}Th, and ^{40}K in heap pad soils. Heap pad soils showed lower levels of 11–29 Bq/kg for ^{238}U and ^{232}Th, and 213–236 Bq/kg for ^{40}K, with absorbed dose rates of 30–32 nGy/h, Ra_{eq} dose rates of 66–70 Bq/kg, gamma index, external hazard index and internal hazard index below 1, and effective doses of 0.15–0.16 mSv/y, confirm that radiological properties of the heap pad soil fall well within the EU-BSS and IAEA safety criteria for unrestricted reuse in building and construction applications. Hence the heap soils are a radiologically sustainable resource that can be incorporated into building materials without exceeding the public dose limit of 1 mSv per year.

III. Thesis

I assessed radionuclide concentrations in water resources (surface waters, boreholes, and hand-dug wells) from the same mining communities. Mean activity concentrations were 1.15±0.21 Bq/L (^{226}Ra), 1.60±0.35 Bq/L (^{228}Th), and 20.70±3.60 Bq/L (^{40}K). The committed effective dose from water ingestion averaged 0.41±0.08 mSv/y, about four times higher than the WHO guideline of 0.1 mSv/y, with maximum values reaching 1.64 mSv/y. Excess lifetime cancer risk (ELCR) averaged 1.59×10^{-3}, above the recommended threshold of 0.39×10^{-3}, presenting an increasing risk for developing cancer if water from these surface water sources are used as drinking water. However, water samples from the borehole and wells screened for gross alpha and beta activities were within WHO and Ghana Standards Authority guidelines making them radiological safe for drinking water.

IV. Thesis

I investigated the possible transfer of radionuclides into rice cultivated in the study areas. Mean concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were 5.03±1.75 Bq/kg, 1.76±0.57 Bq/kg, and 39.10±10.12 Bq/kg, with maximum values of 10.63, 3.80, and 63.88 Bq/kg, respectively. The estimated annual committed effective dose from rice ingestion ranged between 0.016–0.151 mSv/y, well below the 0.3 mSv/y ICRP limit for ingestion, with an average ELCR of 0.291×10^{-3}, significantly lower than the global average of 1.16×10^{-3} for ingestion (ICRP, 2007). This finding indicates that the current dietary habits of the population do not pose a significant radiological risk or risk of developing cancer hence the consumption of rice from the district does not pose a significant radiological health risk to the population.

V. Thesis

I assessed the possibility of natural radionuclides transfer from soil and irrigation water to rice. The findings of the transfer metrics indicated the presence of distinct uptake pathways for the radionuclides. ^{226}Ra demonstrated a high water-to-rice concentration ratio ($CR_W\approx4.37$), thus indicating that irrigation water is an important pathway. In contrast, ^{40}K exhibited a higher soil-to-rice transfer factor ($TF\approx0.12$), and possible additional uptake from the irrigation water ($CR_W\approx1.89$) which is consistent with its uptake from soil as an essential nutrient. Conversely, the ^{232}Th exhibited both a low $TF\approx0.07$ and a $CR_W\approx1.10$, suggesting suboptimal bioavailability. These findings suggest that rice may be used as a bioindicator of environmental radioactivity for radium uptake from water and potassium uptake from soil but is not a reliable bioindicator of thorium.

VI. Thesis

I evaluated the overall radiological risk from soil, water, and rice in the studied communities. Although the total annual effective doses ($\leq$ 1 mSv/y) were within ICRP (2007) limits; the continuous illegal mining with relative high concentration of radium and thorium in the surface water and the irrigation water to the rice farms highlight a potential long-term health risk. This work provides critical baseline data for radiological risk assessment in artisanal mining environments in Ghana and emphasizes the need for regular monitoring, remediation measures, and regulatory oversight to safeguard environmental and public health.

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PUBLICATIONS ACTIVITY

Publications related to the subject of the thesis

Articles published in international referred journals (3)

1. Faanu, Augustine; Tettey-Larbi, Lordford; Akuo-ko, Esther Osei; Gyekye, Prince Kwabena; Kpeglo, David Okoh; Lawluvi, Henry; Kansaana, Charles; Adjei-Kyereme, Serwaa; Efa, Alexander Opoku; Tóth-Bodrogi, Edit; Kovács, Tibor; Shahrokhi, Amin. Radiological landscape of natural resources and mining: Unveiling the environmental impact of naturally occurring radioactive materials in Ghana's mining areas (2024). Heliyon 10: 3 Paper e24959 (2024), https://doi.org/10.1016/j.heliyon.2024.e24959. Rank: Q1. IF: 3.6.
2. Kansaana, Charles; Tettey-Larbi, Lordford; Faanu, Augustine; Sam, Frederick; Akrobortu, Emmanuel; Akomaning-Adofo, Emmanuel; Ampene, Adriana Asare; Osei, Rita Kwabea; Annan, Ruth Araba Tawiah; Tóth-Bodrogi, Edit; Kovács, Tibor; Shahrokhi, Amin. Environmental Radiological Impact and Risk Assessment of Natural Radioactivity at the Heap Leach Facility of Tarkwa Goldmine, Ghana: Radiotoxicity and Public Exposures. Environments 11: 8p. 168 (2024), https://doi.org/10.3390/environments11080168. Rank: Q1. IF: 3.7.
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2. Amin Shahrokhi, Lordford Tettey-Larbi, Serwaa Adjei-Kyereme, Esther Osei Akuo-ko, Thomas Onumah and Tibor Kovács. Radiological impacts of waste managements and mining activities in Ghana: Addressing environmental and public health

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3. Esther Osei Akuo-ko, Amin Shahrokhi, Lordford Tettey-Larbi, Serwaa Adjei-Kyereme, Thomas Onumah, Anita Csordás, and Tibor Kovács. The prospective for radiological sustainability through the reuse of NORM residues in construction materials. Canadian Radiation Protection Association 2025 Annual Conference (CRPA 2025) (2025).
4. Esther Osei Akuo-ko, Francie Otoo, Lordford Tettey-Larbi, Serwaa Adjei-Kyereme, Thomas Onumah, Anita Csordás, and Tibor Kovács. A comprehensive radiological investigation of soils and water resources in artisanal gold mining areas in Ghana. Mining activities vs radiological risks. Canadian Radiation Protection Association 2025 Annual Conference (CRPA 2025) (2025).
5. Tettey-Larbi Lordford, Adjei-Kyereme Serwaa, Onumah Thomas, Tóth-Bodrogi Edit, and Kovács Tibor. Radiological Risk Assessment and Transfer Pathways of Naturally Occurring Radionuclides in Rice Cultivated within Unregulated Artisanal Mining Areas in Ghana. PhD hallgatók anyagtudományi napja XXV Materials science day XXV of PhD students (2025)
6. Esther Osei Akuo-ko, Lordford Tettey-Larbi, Francis Otoo, Anita Csordás, Tibor Kovács. Analysis Of Radionuclides Dissolved in Water Resources Within Gold Mining Areas, Ghana. 7th International Ankara Multidisciplinary Studies Congress (2024).
7. Esther Osei Akuo-ko, Serwaa Adjei-Kyereme, Lordford Tettey-Larbi, Tuvshinsaikhan Ganbaatar, Thomas Onumah, Anita Csordás and Tibor Kovács. Radiological Assessment of Surface Water Resources within Gold Mining Areas, Ghana. PhD hallgatók anyagtudományi napja XXIV, XXIV Material Science Day Conference for PhD Students (2024).
8. Esther Osei Akuo-ko, Serwaa Adjei-Kyereme, Lordford Tettey-Larbi, Thomas Onumah, Anita Csordás, Tibor Kovács. Investigations of Radioactivity Levels in Soils from Various Gold Mining Communities in Eastern Region, Ghana. 6th International Anatolian Scientific Research Congress (2024)
9. Lordford Tettey-Larbi, Esther Osei Akuo-ko, Amin Shahrokhi, Edit Tóth-Bodrogi, Tibor Kovács. The Conception of Radiological Sustainability Possibilities by Reutilization of NORM Residues in Building Materials. 10th International New York Conference on Evolving Trends in Interdisciplinary Research & Practices, (2024).

10. Lordford Tettey-Larbi, Esther Osei Akuo-ko, Gergely Tóth, Augustine Faanu, Amin Shahrokhi, Edit Tóth-Bodrogi, Tibor Kovacs. Assessments of Naturally Occurring Radionuclides in Soils and Water in Some Mining Communities in Ghana. International Radiation Protection Association Health Physics Society, 16th International Congress, 69th Annual HPS Meeting (2023).
11. Lordford Tettey-Larbi, Esther Osei Akuo-ko, Tuvshinsaikhan Ganbaatar, Gergely Tóth, Máté Novák, Serwaa Adjei-Kyereme, Thomas Onumah, Edit Tóth-Bodrogi, Tibor Kovács. Gross Alpha and Beta Activity Screening in Water: A Baseline Study in the Vicinity of a Gold Mine in Ghana. PhD hallgatók anyagtudományi napja XXIV, XXIV Material Science Day Conference for PhD Students (2024).
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13. Esther Osei Akuo-Ko, Lordford Tettey-Larbi, Francis Otoo, Anita Csordás, Tibor Kovács. Surveying the Quality of Groundwater Resources in Gold Mining Communities in Eastern Region of Ghana. 4th International Mediterranean Scientific Research Congress (2023).
14. Esther Osei Akuo-ko, Lordford Tettey-Larbi, Francis Otoo, Aissa Benselhoub, Anita Csordás, Amin Shahrokhi, Tibor Kovács. Radiological safety of water resources within selected gold mining areas in the Eastern region of Ghana. The 4th International Symposium on Mineral Industry and Environment (4SIMINE23) (2023)
15. Lordford Tettey-Larbi, Esther Osei Akuo-ko, Tuvshinsaikhan Ganbaatar, Gergely Tóth, Máté Novák, Amin Shahrokhi, Edit Tóth-Bodrogi, Tibor Kovács. Investigating the Naturally Occurring Radionuclide Activity Concentrations in Ghana's Mining Communities. 5th International Black Sea Modern Scientific (2023).
16. Lordford Tettey-Larbi, Esther Osei Akuo-ko, Tuvshinsaikhan Ganbaatar, Gergely Tóth, Máté Novák, Amin Shahrokhi, Edit Tóth-Bodrogi, Tibor Kovács. Environmental Impact of Naturally Occurring Radionuclides in Ghana's Mining Areas. PhD hallgatók anyagtudományi napja XXIII, Materials science day XXIII of PhD students (2023).
17. Lordford Tettey-Larbi, Esther Osei Akuo-ko, Edit Tóth-Bodrogi, Tibor Kovács. Naturally occurring radionuclides contamination of River Pra due to illegal mining

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Other publications

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1. Dickson-Agudey, Philomena; Tettey-Larbi, Lordford; Adjei-Kyereme, Serwaa; Lawluvi, Henry; Asare, Eric; Osei, Rita Kwabea; Ampene, Andriana Asare; Shahrokhi, Amin. Radiological risk assessment of natural radioactivity in imported rice consumed in Ghana and its implications for food safety and public health. Scientific Reports, **16**, 6266 (2026), https://doi.org/10.1038/s41598-026-37317-0. Rank: Q1. IF: 4.3
2. Akuo-ko, Esther Osei; Otoo, Francis; Glover, Eric Tetteh; Amponsem, Eunice; Tettey-Larbi, Lordford; Ganbaatar, Tuvshinsaikhan; Csordás, Anita; Shahrokhi, Amin; Kovács, Tibor. Radiological Implications of Industrial Activities on Soil and Water: An Environmental Analytical Chemistry Perspective in Artisanal Gold-Mining Regions of Atiwa West. Applied Sciences-Basel 15: 18 p. 9857 (2025). Rank: Q2. IF: 2.5.
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6. Abdalsattar, Kareem Hashim; Laith, Ahmen Najam; Tettey-Larbi, Lordford. A Study of Radon Concentration in Different Brands Tobacco Cigarette in Iraqi Market, Influencing Factors and Lung Cancer Risk. International Journal of Science and Technology 5; 10 pp. 1-8, 8 p. (2015).
7. Adukpo, O. K.; Faanu, A.; Lawluvi, H.; Tettey-Larbi, L.; Emi-Reynolds, G.; Darko, E. O.; Kansaana, C.; Kpeglo, D. O.; Awudu, A. R. Distribution and assessment of radionuclides in sediments, soil and water from the lower basin of river Pra in the Central and Western Regions of Ghana. Journal of Radioanalytical and Nuclear Chemistry 303: 3 pp 1979-1685. (2015), https://doi.org/10.1007/s10967-014-3637-5. Rank: Q2. IF: 1.6
8. Tettey-Larbi, L.; Poku, L. O.; Darko, E. O.; Faanu A.; Appiah, A. A.; Baidoo, I. K.; Osei, R. K. Determination of the Concentration of Potassium in Lippia Multiflora and Bridelia Ferruginea for the Treatment of High Blood Pressure (Hypertension). International Journal of Science and Technology 5: 1 pp. 24-27, 4 p. (2015).
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10. Tettey-Larbi, L.; Darko, E. O.; Schandorf, C.; Appiah, A. A.; Sam, F.; Faanu, A.; Kpeglo, D. O.; Lawluvi, H.; Agyeman, B. K.; Kansaana, C.; Amoah, P. A.; Osei, R. K.; Agalga, R.; Osei, S. Gross Alpha and Beta Activity and Annual Committed Effective Doses due to Natural Radionuclides in Some Medicinal Plants commonly

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1. Adjei-Kyereme Serwaa, Tettey-Larbi Lordford, Onumah Thomas, Tóth-Bodrogi Edit, and Kovács Tibor. Evaluation of Fission and Activation Products Contamination in Fish from Aquatic Systems within the Semipalatinsk Test Site. PhD hallgatók anyagtudományi napja XXV Materials science day XXV of PhD students (2025)
2. Amin Shahrokhi, Lordford Tettey-Larbi, Esther Osei Akuo-ko, and Tibor Kovács. Brief overview on the potential possibility of integrating nanotechnology for corrosion and material enhancement in nuclear industry applications. 13th International Conference on Radiation, Natural Sciences, Medicine, Engineering, Technology and Ecology, RAD 2025 Conference, (2025).
3. Amin Shahrokhi, Lordford Tettey-Larbi, Serwaa Adjei-Kyereme, Esther Osei Akuo-ko, Thomas Onumah and Tibor Kovács. An Overview of the Feasibility of Leveraging Deep Learning for Environmental Radioactivity: Opportunities, Challenges, and Interdisciplinary Solutions. 8th International Conference on Environmental Radioactivity (ENVIRA 2025) (2025)
4. Amin Shahrokhi, Esther Osei Akuo-ko, L. Maud Naa Dedei Palm, Lordford Tettey-Larbi, Serwaa Adjei-Kyereme and Tibor Kovács. Sustainability – socioeconomic and environmental effects of climate-induced seawater quality changes on coastal fisheries: A case study on temperature and salinity shifts. 19th International Conference on Chemistry and the Environment – ICCE 2025 Environmental Chemistry for Sustainability (2025)
5. Lordford Tettey-Larbi, Serwaa Adjei-Kyereme, Thomas Onomah, Amin Shakrokhi, Edit Tóth-Bodrogi, and Tibor Kovács. Review of the Radiological Excess Lifetime Cancer Risk Assessment in Tobacco Cigarette. 12th International New York Conference on Evolving Trends in Interdisciplinary Research and Practices (2025)

6. Máté Novák, Zsolt Homoki, Lordford Tettey-Larbi, Gergely Tóth, Edit Tóth-Bodrogi, Anita Csordás and Tibor Kovács. Determination of Radon Exhalation and Emanation of Hungarian Soil Samples. Radiation Environment and Medicine (2025).
7. Sarpong Linda, Abrefah Rex, Tettey-Larbi Lordford and Nooni Isaac. Long term Spatio-Temporal Analysis of Climate Trends in Ghana: Implication for Nuclear Power Plant siting and sustainability. International Conference on Resilience of Nuclear Installations against External Events from a Safety Perspective – Focus on Climate Change. NIRC - 2025 (2025).
8. Tóth Gergely, Novák Máté, Homoki Zsolt, Tettey-Larbi Lordford, Gyöngyösi Csaba, Csordás Anita and Kovács Tibor. Radium Determination in Spring Waters of Veszprém County by Liquid Scintillation. Radiation Environment and Medicine (2025).
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