AKENTEN APPIAH – MENKA UNIVERSITY OF SKILLS TRAINING AND ENTREPRENEURIAL DEVELOPMENT

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ECOLOGICAL AND HUMAN HEALTH RISKS OF POTENTIALLY TOXIC ELEMENTS AND NATURALLY OCCURRING RADIOACTIVE ELEMENTS IN FOOD CROPS FROM SOILS IN MAMPONG, GHANA

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A thesis submitted to the Department of Chemistry, Faculty of Science, Akenten Appiah-Menka University of Skill Training and Entrepreneurial Development in partial fulfilment of the requirements for the award of a Master of Philosophy degree in Chemistry Education

APRIL, 2025

DECLARATION

I hereby declare that this thesis is the outcome of research work undertaken by me towards the MPhil degree and to the best of my knowledge, contains no work previously published nor material accepted for another degree of the University except where due acknowledgement has been given in the text.

Candidate's Name: Ofori Donkor Juliet

Signature: ……………………………………. Date: …………………………….

Supervisor's Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development

Principal Supervisor's Name: Prof. Kofi Sarpong

Signature ……………………………………… Date ……………………………

Co-Supervisor's Name: Dr. Opoku Gyamfi

Signature ………………………………………… Date ………………………………

DEDICATION

This work is dedicated to my family and Mr. Edward Ankapong, who encouraged me to embark on this academic journey and has been a source of inspiration in my academic pursuit.

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This work has been made possible out of the amazing grace of the Lord God Almighty. Special thanks go to my supervisors, Prof. Kofi Sarpong and Dr. Opoku Gyamfi, for their immeasurable support, guidance, patience, and love throughout this work. I say God bless you for all your loss.

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ABSTRACT

This study examines the levels, spatial distribution, and health risks of naturally occurring radioactive materials (NORMs) and potentially toxic elements in agricultural soils and food crops (cassava, yam, and cocoyam) in Mampong Municipality. The research focuses on uranium-238, thorium-232, potassium-40, and heavy metals such as cadmium, chromium, lead, and arsenic, which pose environmental and health risks. The study's findings reveal that the soils are mildly acidic (average pH ~ 6.25), a condition conducive to increased metal solubility and bioavailability, which enhances the transfer of metals to plants. Key physicochemical parameters, such as electrical conductivity and organic carbon content, indicate that soils have low ionic contamination but varying capacities for metal retention and mobility. Potentially toxic elements concentrations in soils exhibited a consistent trend (Mn > Zn > Cr > Ni > Cu > Pb > Cd > As), with manganese and zinc as the most abundant, though potentially harmful elements like cadmium, chromium, and lead exceeded permissible limits in several locations. Mn concentrations, although the highest among metals tested, generally remained within safe levels and posed lower risks to human health and the environment. Zn concentrations were notable but also largely within acceptable limits, indicating moderate environmental concerns. However, the comparison highlights the variability of these metals' risks depending on location and other soil factors such as pH and organic content. Radionuclide measurements identified moderate activity concentrations of uranium-238, thorium-232, and potassium-40, with calculated hazard indices generally within acceptable limits but with specific areas showing elevated risks. The study found high metal transfer rates from soil to crops, particularly for manganese, chromium, zinc, and cadmium. Cocoyam showed the highest bioaccumulation, with cadmium and chromium posing non-carcinogenic risks to children. Lifetime cancer risk assessments suggest long-term exposure concerns. The research highlights the need for continuous environmental monitoring and regulatory interventions to mitigate contamination risks. Public awareness initiatives and stricter policies are recommended to protect food safety, human health, and the ecosystem.

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Food crops play an essential role in sustaining the global population and animals, serving as primary sources of nutrition and possessing medicinal properties. The contamination of these crops by potentially toxic elements (PTEs) and naturally occurring radioactive elements (NOREs) poses significant health risks and threatens food security (Dwivedi et al., 2017). As agricultural production continues to expand globally, ensuring the safety of food crops remains a critical challenge, particularly in countries such as Ghana, where local agricultural practices are influenced by environmental factors (Adomako & Ampadu, 2015).

Food production is vital to feeding a growing global population, which is projected to reach 9.7 billion by 2050 (WHO & FAO, 2023). Food crops such as maize, rice, and wheat constitute a large proportion of global agricultural output, providing essential nutrients for human health and livestock production. The Food and Agriculture Organization (FAO) reported that the global production of primary crops reached approximately 9.6 billion tonnes in 2022, marking a 56% increase since 2000 (WHO & FAO, 2023). In Ghana, agriculture contributes significantly to the national economy, with crop production accounting for nearly 54% of the agricultural GDP (GSS, 2021). Asante Mampong, located in the Ashanti Region, is known for its agricultural activities, particularly in the cultivation of maize, cassava, yam, and plantain. These staple crops are vital for local food security and serve as economic drivers for smallholder farmers.

Beyond providing essential nutrients, many food crops also possess medicinal properties.

For example, turmeric contains curcumin, a compound with anti-inflammatory and antioxidant properties, while garlic is known for its cardiovascular benefits (Mansi Paliwal et al., 2023). Traditional medicine systems, particularly in Africa, rely heavily on medicinal plants for treating various ailments, further highlighting the importance of food crops beyond nutrition. Ghana, like many other African countries, incorporates medicinal plants into its healthcare system, making food crops an integral part of both sustenance and traditional medicine (Mudau et al., 2022).

Globally, agricultural production has increased significantly in response to rising food demand. According to FAO statistics, staple crops such as sugarcane, maize, wheat, and rice collectively account for nearly half of global food crop production (WHO & FAO, 2023). Meat production has also seen a notable rise, increasing by 55% between 2000 and 2022, with poultry leading the increase (WHO & FAO, 2023). In Ghana, agricultural expansion has been central to economic development, with key areas like Asante Mampong contributing to national food production. However, environmental concerns, including soil degradation and contamination by heavy metals and radioactive elements, pose challenges to sustainable crop cultivation (McGrath et al., 2014).

Agriculture remains a significant economic sector worldwide. In 2022, the global agricultural sector contributed approximately $3.8 trillion to the global economy, representing an 89% increase in real terms over the past two decades (World Bank, 2023). Despite this growth, the proportion of the workforce engaged in agriculture has declined, with the global percentage dropping from 40% in 2000 to 26% in 2022 (ILO, 2023). In Ghana, agriculture employs over 44% of the labour force, with smallholder farmers playing a crucial role in food production (Ghana Statistical Service, 2022). The agricultural economy of Asante Mampong relies heavily on crop farming, providing income for rural households while also facing challenges related to soil contamination and land-use changes.

The presence of PTEs and NOREs in food crops is of growing concern, as these contaminants can have detrimental effects on human health and agricultural sustainability. Potentially Toxic Elements (PTEs) such as arsenic, cadmium, lead, chromium, and mercury are naturally present in the environment but can become hazardous when their concentrations exceed safe limits. This may be due to human activities such as mining and improper waste disposal (Kumar et al., 2019). Similarly, NOREs, including uranium, thorium, and radon, can accumulate in agricultural soils and water sources, leading to their uptake by food crops (UNSCEAR, 2022a).

The contamination of food crops by PTEs and NOREs occurs through multiple pathways. Soil contamination results from industrial waste disposal, mining, and the excessive use of fertilizers and pesticides. Crops grown in contaminated soils absorb these elements, leading to their accumulation in edible plant parts (Chen et al., 2024). Water contamination occurs when irrigation water is polluted with industrial effluents, leachates from landfills, or naturally occurring deposits of heavy metals and radionuclides (Tuo et al., 2020a). Additionally, atmospheric deposition from mining and industrial emissions can contribute to the contamination of soil and crops, further exacerbating the risk of exposure (S. Wang et al., 2020).

The consumption of contaminated food crops can lead to serious health effects. Arsenic exposure is associated with skin lesions, cardiovascular diseases, and an increased risk of cancer (WHO, 2021). Lead poisoning can impair neurological development in children, leading to cognitive deficits and behavioural problems (CDC, 2023). Cadmium accumulation in the body affects kidney function and bone health, while mercury toxicity can damage the nervous system. Exposure to radioactive elements, such as uranium and thorium, increases the risk of cancer and genetic mutations (IAEA, 2022). In Ghana, studies have reported elevated levels of heavy metals in agricultural soils and food crops, particularly in regions with mining activities (Darko et al., 2020). This underscores the need for regular monitoring of food safety, particularly in agricultural zones like Asante Mampong, where farmers rely on natural water sources for irrigation. Addressing food crop contamination requires integrated approaches that combine environmental monitoring, regulatory policies, and sustainable agricultural practices.

1.2 Problem Statement

Food crop contamination by PTEs and NOREs is an emerging global concern with severe implications for human health, environmental sustainability, and economic stability. While food production has increased significantly in response to global population growth, the quality and safety of agricultural products are increasingly threatened by contamination from industrial activities, mining, and unsustainable agricultural practices. Ghana, particularly in areas like Asante Mampong, faces challenges associated with soil and water contamination due to environmental pollutants. Despite being a non-mining area, Asante Mampong is susceptible to atmospheric deposition, water source contamination, and agricultural practices that contribute to the accumulation of PTEs and NOREs in food crops.

The bioaccumulation of PTEs such as arsenic, lead, cadmium, chromium, and mercury, as well as NOREs like uranium and thorium, poses significant health risks. Studies have shown that prolonged exposure to these elements through food consumption can lead to adverse health effects, including cancer, neurological disorders, cardiovascular diseases, and organ damage (WHO, 2022; CDC, 2023). In Ghana, Studies have indicated an increase in health-related issues stemming from pollution caused by these metals (Ali et al. 2019; Asiminicesei et al. 2020; Khan et al. 2021). According to the study, there were three cases of neoplasm in every hundred thousand individuals, with five cases in children. Similarly, (Siaw et al. 2020) identified the pollution of cocoyam, plantain, and water with arsenic, chromium, and nickel in Kibi – a major mining town in Ghana. Another study (Baah et al., 2021) Recently, a high cancer risk was documented linked with the consumption of plantain grown in Abuakwa South Municipal of Ghana due to pollution of the soil with toxic elements such as chromium, nickel, and lead. Human activities have significantly impacted agricultural land, leading to various environmental, economic, and social challenges. Some of the key problems include soil degradation, chemical overuse, such as the use of fertilizer and pesticides. However, there is limited research specifically addressing the extent of food crop contamination in non-mining areas like Asante Mampong, where environmental exposure routes remain poorly understood (Amuah et al., 2021).

Furthermore, there is a gap in the implementation of strict policies to regulate soil and water quality in agricultural zones. Although agencies such as the Ghana Environmental Protection Agency (EPA) and the Ministry of Food and Agriculture (MoFA) have established guidelines for agricultural safety, enforcement remains inconsistent (Crozier et al., 2018). The lack of systematic assessment and risk mitigation strategies worsens the potential for human exposure to toxic elements, threatening both food security and economic stability in farming communities. Addressing this issue requires interdisciplinary research, policy interventions, and sustainable agricultural practices to mitigate contamination risks and ensure the long-term safety of food production systems in Ghana. Given the critical role of food crops in public health and economic development, it is imperative to investigate the extent of PTE and NORE contamination in agricultural regions like Asante Mampong.

1.3 Objectives of the Study

1.3.1 Main Objective

The main objective of this study was to assess the ecological and human health risks associated with potentially toxic elements (PTEs) and naturally occurring radioactive materials (NORMs) in food crops cultivated on soils from Asante Mampong, Ghana, to ensure the safety of food consumption and promote sustainable agricultural and environmental management practices.

1.3.2 Specific Objectives

The specific objectives of the study shall be:

1. To determine the concentrations of potentially toxic elements (PTEs), including cadmium, lead, chromium, and arsenic, in soils and selected food crops (cassava, cocoyam, and yam) from Asante Mampong.
2. To measure the activity concentrations of naturally occurring radioactive materials (NORMs), including ^{238}U, ^{232}Th, and ^{40}K, in soils and selected food crops from the study area.
3. To evaluate the ecological risks posed by the presence of PTEs and NORMs in the agricultural soils of Asante Mampong.

4. To assess the potential non-carcinogenic and carcinogenic health risks to humans from the ingestion of food crops contaminated with PTEs and NORMs.
5. To investigate the relationship between soil physicochemical properties and the uptake of PTEs and NORMs by food crops in the study area.

1.4 Significance of the Study

This study is significant as it provides scientific insights into the contamination of food crops by PTEs and NOREs, particularly in non-mining agricultural regions like Asante Mampong. By identifying contamination levels and potential sources, the study would contribute to a better understanding of the environmental factors affecting food safety. The findings would be crucial for policymakers, environmental agencies, and agricultural stakeholders in developing and implementing effective strategies to mitigate contamination risks.

The study would also have significant public health implications. Assessment of health risks associated with consuming contaminated food crops would inform regulatory bodies such as the Ghana Environmental Protection Agency (EPA) and the Ministry of Food and Agriculture (MoFA) on necessary interventions. Additionally, it would raise awareness among farmers and consumers about best practices to minimize exposure to toxic elements and radionuclides, promoting food safety and public health. Economically, the study would support the sustainability of Ghana’s agricultural sector by providing data-driven recommendations to enhance soil and water management practices. Ensuring safe food production would help maintain the marketability of agricultural products, prevent potential economic losses, and sustain the livelihoods of farmers in Asante Mampong and other agricultural regions.

Ultimately, this study would play a vital role in guiding policies and interventions aimed at safeguarding food security, environmental sustainability, and public health in Ghana and beyond.

1.5 Limitations of the Study

Despite the significance of this study, certain limitations must be acknowledged. One major limitation is the scope of the study, which focuses primarily on Asante Mampong, a non-mining area in Ghana. While this provides valuable localized data, the findings may not be entirely generalizable to other regions with different environmental and agricultural conditions. Further research in diverse ecological settings is necessary to obtain a more comprehensive understanding of food crop contamination across Ghana and beyond.

Another limitation is the reliance on available sampling techniques and analytical methods for detecting PTEs and NOREs in food crops. While modern laboratory techniques provide high levels of accuracy, variations in sample collection, preparation, and instrumentation may introduce uncertainties in the results. Additionally, the study may not account for all possible contamination sources, such as long-term soil accumulation, atmospheric deposition from distant sources, or interactions between multiple pollutants.

Moreover, the study primarily focuses on the contamination levels and potential health risks of PTEs and NOREs but does not fully explore the socio-economic and policy dimensions of food crop contamination. While recommendations will be provided, the effectiveness of policy implementation and stakeholder engagement will require further investigation beyond the study’s timeframe.

Lastly, external factors such as climate change, land-use changes, and evolving agricultural practices could influence contamination patterns over time. The study represents a snapshot of contamination levels at a specific period, and continuous monitoring will be necessary to track long-term trends and develop adaptive mitigation strategies. Despite these limitations, the study remains a crucial step toward understanding and addressing the risks associated with PTE and NORE contamination in food crops.

CHAPTER TWO

LITERATURE REVIEW

2.1 Global Overview of Food Crop Production

Global food crop production is a critical component of global food security and economic development. The Food and Agriculture Organization (FAO) estimates that by 2050, food production must increase by 70% to sustain the growing global population ((WHO & FAO, 2023). Key staple crops such as rice, wheat, maize, and potatoes account for the majority of global calorie consumption. Despite advancements in agricultural technology, challenges such as climate change, soil degradation, and contamination by potentially toxic elements (PTEs) and naturally occurring radioactive elements (NOREs) remain significant (Bennett *et al.,* 2022). In Ghana, agriculture remains a dominant sector, contributing about 19.7% to the Gross Domestic Product (GDP) (Ghana Statistical Service, 2022). Asante Mampong, a major agricultural region in Ghana, plays a crucial role in food production. However, contamination from PTEs and NOREs poses potential risks to food security and public health (Amponsah *et al.*, 2023).

2.2 Importance of Food Crops in Human and Animal Nutrition

Food crops provide essential nutrients that support human and animal health. They serve as primary sources of carbohydrates, proteins, vitamins, and minerals. Dietary intake of fruits, vegetables, and whole grains has been linked to the reduction of chronic diseases such as cardiovascular diseases, diabetes, and certain cancers (Micha et al., 2022). Additionally, crops such as maize, soybean, and sorghum are widely used in animal husbandry, supporting global livestock production (Ghimire et al., 2021). However, contamination by PTEs and NOREs may compromise the nutritional quality of these crops, posing health risks to both humans and animals.

2.3 Medicinal Properties of Food Crops

Many food crops possess medicinal properties due to their bioactive compounds. Phytochemicals such as flavonoids, alkaloids, and polyphenols exhibit antioxidant, anti-inflammatory, and antimicrobial activities (Salehi et al., 2021). For instance, turmeric (Curcuma longa) contains curcumin, which has potent anti-inflammatory and anticancer properties, while garlic (Allium sativum) has been shown to lower blood pressure and cholesterol levels (Rahman et al., 2022). However, contamination of these medicinal crops with PTEs and NOREs may reduce their therapeutic efficacy and introduce toxic effects.

2.4 Economic Importance of Crop Production

Crop production plays a vital role in economic growth by providing employment, income, and foreign exchange earnings. In Ghana, agriculture employs over 50% of the population and significantly contributes to poverty reduction (GSS, 2022). Export crops like cocoa, cashew, and shea butter are major contributors to Ghana’s economy. However, contamination of food crops with PTEs and NOREs can result in trade restrictions, economic losses, and non-compliance with international food safety standards (Obiri et al., 2023).

2.5 Potentially Toxic Elements

Potentially toxic elements (PTEs) are naturally occurring or anthropogenic elements that, at elevated concentrations, pose significant risks to human health and the environment (Joshi et al., 2022). Examples of these elements include cadmium, lead, arsenic, chromium, and mercury. While some PTEs, such as zinc and copper, are essential trace nutrients for biological processes, their toxicity becomes pronounced when their levels exceed critical thresholds. This dual nature of PTEs underscores the need for careful monitoring and management to mitigate their adverse effects (Alloway, 2013).

2.5.1 Sources of Potentially Toxic Elements in Agricultural Soils

Potentially toxic elements (PTEs) are elements that, when present in elevated concentrations, can harm human health, ecosystems, and agricultural productivity. These elements include cadmium, lead, arsenic, chromium and mercury. While some PTEs are naturally occurring, their levels in agricultural soils can be significantly influenced by various anthropogenic activities. Identifying and understanding the sources of PTEs is crucial for developing effective strategies to mitigate their presence and reduce their harmful effects on both the environment and public health.

2.5.1.1 Natural Sources of Potentially Toxic Elements

Potentially toxic elements naturally exist in the Earth's crust, and their presence in soils can be attributed to geological processes (Aswal et al., 2023). These processes include the weathering of parent rocks, volcanic activity, and erosion. The concentration of PTEs in soils is largely determined by the local geological composition, with areas rich in metal ores, such as gold, copper, and iron, being more susceptible to elevated PTE levels.

The breakdown of rocks over time releases metals like lead, cadmium, and arsenic into the surrounding soils. For instance, areas with naturally high levels of arsenic in the bedrock may result in elevated arsenic concentrations in soils and groundwater (Yin et al., 2022). Erosion also plays a role in redistributing these elements across vast areas, sometimes leading to the contamination of agricultural land.

Volcanic eruptions can release metals such as mercury and arsenic into the environment. While the deposition of these metals from volcanic ash is generally localized, it can still contribute to the accumulation of PTEs in soils, particularly in volcanic areas (Yin et al., 2022).

2.5.1.2 Anthropogenic Sources of PTEs

Anthropogenic activities are significant contributors to PTE contamination in agricultural soils. Human activities such as mining, industrial processes, waste disposal, and the use of agricultural chemicals can elevate the concentrations of toxic elements in the environment, often exceeding the naturally occurring levels. Mining operations, particularly those that extract gold, copper, and other metals, release large quantities of PTEs into the surrounding environment. The use of chemicals such as cyanide and mercury in gold extraction, for example, has been shown to contaminate both soil and water (Malone et al., 2023).

The use of chemical fertilizers and pesticides is a widespread practice in agriculture to enhance crop yield and control pests. However, certain fertilizers, such as phosphate fertilizers, contain trace amounts of cadmium, which can accumulate in soils over time. Long-term use of such fertilizers leads to the build-up of cadmium in agricultural soils, posing a risk to both crop safety and public health (P. Wang et al., 2019). Similarly, pesticides often contain heavy metals like lead and mercury, which can leach into soils and accumulate in the food chain.

Improper disposal of industrial and household waste, including e-waste, sewage sludge, and hazardous chemicals, is a significant source of PTEs in urban and agricultural soils.

For instance, the burning of e-waste releases lead and mercury into the atmosphere, which can eventually settle on soils and affect their quality. Additionally, industrial emissions from smelting and manufacturing processes can deposit PTEs onto surrounding lands, contributing to soil contamination (Jeong et al., 2021)

Urbanization contributes to PTE contamination through vehicle emissions, construction activities, and waste disposal. Lead, for example, is commonly found in urban soils due to the historical use of leaded gasoline and the continued deposition of industrial emissions. Soil contamination from traffic pollution, including zinc, copper, and lead, is particularly evident in cities with high traffic density (Sager, 2020).

2.5.1.3 Climate Change and Atmospheric Deposition

Climate change can exacerbate the release and mobility of PTEs in soils. Increased rainfall, for instance, can lead to the leaching of PTEs into groundwater, whereas higher temperatures may accelerate the breakdown of contaminated soil particles, making PTEs more bioavailable to plants. Additionally, the changing atmospheric conditions can influence the deposition of airborne PTEs, such as mercury, onto agricultural lands (Chen et al., 2024).

2.5.2 Fate and Transport of PTEs in the Environment

Potentially toxic elements (PTEs) are metals and metalloids that, when present in high concentrations, pose a risk to human health, wildlife, and ecosystems (I. Khan et al., 2024). The fate and transport of these elements in the environment are influenced by their physical and chemical properties, such as solubility, bioavailability, and persistence.

The fate of PTEs in the environment is largely governed by their chemical form and interactions with environmental factors. PTEs typically exist in various oxidation states, and their mobility and toxicity are influenced by these forms. For example, arsenic can exist in both the trivalent (As^{3+}) and pentavalent (As^{5+}) oxidation states, with As^{3+} being more toxic and mobile in the environment. Similarly, chromium exists in both the hexavalent (Cr^{6+}) and trivalent (Cr^{3+}) forms, with Cr^{6+} being more soluble and thus more likely to contaminate groundwater (USEPA, 2011). The transformation between these forms often occurs in response to environmental factors such as pH, redox potential, and microbial activity.

Redox reactions play a crucial role in the transformation and mobility of PTEs. For example, in anoxic environments, the reduction of Cr^{6+} to Cr^{3+} can decrease its solubility and toxicity, making it less mobile in soils (Qu et al., 2019). Similarly, the reduction of mercury (Hg) from its ionic form (Hg^{2+}) to elemental mercury (Hg^0) can facilitate its transport through the atmosphere, as Hg^0 is volatile and can travel long distances before being redeposited on terrestrial or aquatic ecosystems.

Potentially toxic elements can also form complexes with organic and inorganic substances in the environment. These complexes can affect the solubility and mobility of the elements. For example, cadmium often forms complexes with organic matter in soils, which can enhance its retention and reduce its leaching into groundwater (Kicińska et al., 2022). On the other hand, lead (and other PTEs can bind to soil particles through sorption processes, potentially limiting their bioavailability but also making them persistent in the environment.

2.5.2.2 Transport Mechanisms in the Environment

Once released into the environment, PTEs can be transported through various pathways like soil, water, air, and biota. Each medium presents different transport dynamics that influence the extent and direction of PTE contamination.

In soils, PTEs are primarily transported through water infiltration, surface runoff, and soil erosion. The mobility of PTEs in soils is influenced by the soil's texture, organic matter content, and pH. For example, acidic soils tend to enhance the mobility of metals like copper and zinc, whereas alkaline soils may reduce their solubility (Pikuła & Stępień, 2021). During heavy rainfall, PTEs can be washed off the soil surface and carried to nearby water bodies via surface runoff or erosion, leading to widespread contamination.

Water is one of the most important transport mechanisms for PTEs. Contaminants can be transported via both surface water (rivers, lakes) and groundwater (aquifers). In surface water, PTEs are transported primarily as dissolved ions or particulate matter, depending on their chemical form. For instance, arsenic and cadmium are highly mobile in water as dissolved ions, especially in acidic conditions (Manzoor, 2020). In groundwater, PTEs can move with the water flow, often entering drinking water sources. Contaminated groundwater can persist for decades, posing a long-term risk to ecosystems and human populations.

PTEs can also be transported through the atmosphere. This is particularly true for elements like mercury, which is emitted into the atmosphere in its elemental form (Hg^0) from sources such as coal combustion, mining activities, and waste incineration. Mercury vapour can travel long distances before being deposited on land or water through wet or dry deposition. Once deposited, it can enter food chains through the bioaccumulation process (United Nations Environment Programme, 2019). Lead and cadmium can also be transported through the atmosphere, particularly from industrial sources, and can be deposited onto surrounding areas, contaminating soils and water bodies.

2.5.2.3 Bioavailability and Uptake by Organisms

The bioavailability of PTEs, or the extent to which they are accessible to organisms for uptake, is a key factor influencing their toxicity and transport. Once in the environment, PTEs can enter food webs through plants, water, and soil organisms.

Potentially toxic elements can be absorbed by plants through their roots from contaminated soils or water. The extent to which a plant takes up PTEs depends on various factors, including the chemical form of the element, the soil pH, and the plant’s physiological characteristics. For example, cadmium is readily absorbed by crops like rice and vegetables, leading to contamination (Mensah et al., 2024). In contrast, some plants, known as hyperaccumulators, can concentrate high levels of PTEs without suffering toxic effects, which can be exploited for phytoremediation purposes.

Herbivores that consume contaminated plants and other organisms at higher trophic levels may accumulate PTEs in their tissues, leading to biomagnification. For example, mercury can biomagnify in aquatic food chains, with small fish accumulating mercury, which is then passed on to larger fish and ultimately to humans who consume them (Nandomah & Tetteh, 2024). In humans, chronic exposure to PTEs, particularly through food, water, and air, can lead to serious health problems, including neurological disorders, kidney damage, and cancer (Ghane et al., 2022).

2.5.2.4 Factors Influencing the Fate and Transport of PTEs

Several environmental factors play a role in determining the fate and transport of PTEs. The pH and redox conditions can greatly influence the solubility, mobility, and toxicity of PTEs. Acidic conditions, for example, increase the solubility of many heavy metals, making them more mobile in water and soil (Hooda et al., 2022). Conversely, alkaline conditions can lead to precipitation and immobilization of some PTEs.

Climate change can impact the fate and transport of PTEs by altering rainfall patterns, temperature, and the frequency of extreme weather events such as floods and droughts. Increased rainfall can lead to higher surface runoff, while extreme droughts can concentrate PTEs in shrinking water sources (Ponting et al., 2021). Land-use practices, including agriculture, industrialization, and mining, can significantly alter the distribution and mobility of PTEs. Mining activities can introduce large quantities of PTEs into the environment, while agriculture can influence the transport of PTEs through the use of contaminated water for irrigation or through fertilization practices (Siaw et al., 2020).

2.6 Naturally Occurring Radioactive Materials (NORMs)

Naturally Occurring Radioactive Materials (NORMs) are radioactive elements that naturally exist in the Earth’s crust and are present in varying concentrations in soil, water, air, and living organisms. These materials can be traced back to the primordial elements formed during the creation of the Earth. NORMs include elements like uranium, thorium, and radon, which emit radiation as they decay over time into various daughter products. While the presence of NORMs is a natural occurrence, the increased mining, industrial activities, and use of certain materials have led to concerns about their environmental and health impacts. NORMs are radioactive elements that occur naturally in the environment, and their radioactive decay produces ionizing radiation. Some of the most common NORMs include:

- **Uranium**: Uranium, an actinide metal, is a radioactive element that can be found in soil, rocks, and water. It is commonly found as a mixture of isotopes, with uranium-238 being the most abundant. Uranium decays through a series of radioactive transformations, ultimately leading to the production of radon gas.
- **Thorium**: Like uranium, thorium is an actinide metal found in soil and rock. It is more abundant than uranium in some geological formations. Thorium also undergoes radioactive decay to produce radon and other radioactive isotopes.
- **Radon**: Radon is a colourless, odourless, and tasteless radioactive gas that is produced from the decay of uranium and thorium. It is a significant health concern because it can accumulate in indoor environments, particularly in poorly ventilated spaces like basements. Long-term exposure to high concentrations of radon has been linked to lung cancer.
- **Potassium-40**: Potassium-40 is a naturally occurring isotope of potassium, which 2wis present in all living organisms and in the environment. It is a low-level emitter of radiation and is responsible for some of the natural background radiation to which humans are exposed.

2.6.1 Types and Sources of NORMs in Agricultural Soils

The presence of NORMs in agricultural soils is influenced by several natural and anthropogenic sources. While NORMs are naturally occurring, human activities such as mining, agriculture, and industrial processes can lead to the concentration and redistribution of these materials in soil and other environmental media.

The primary source of NORMs in agricultural soils is the Earth's geology. Uranium, thorium, and their decay products, including radium and radon, are present in varying concentrations in different types of soil and rock. Soils in regions with high concentrations of uranium-rich rocks, such as granite, shale, and certain types of sandstone, may have elevated levels of NORMs. Similarly, soils derived from phosphate rocks, which contain uranium and thorium, may also be enriched in NORMs. Natural weathering processes break down rocks containing NORMs, releasing these materials into the surrounding soil. This process is particularly significant in areas where soil formation involves the erosion of uranium-rich or thorium-rich rocks. The weathering of granite, for example, often leads to the release of radon and radium into the soil, which can subsequently be taken up by plants and animals.

Agricultural practices can introduce or concentrate NORMs in soils through the use of contaminated water, fertilizers, and pesticides. For example, phosphate fertilizers, which are derived from phosphate rock, can contain elevated levels of uranium and radium, leading to the accumulation of these materials in agricultural soils. Similarly, the use of contaminated irrigation water can introduce radon, radium, and uranium into agricultural areas. In regions with high natural concentrations of NORMs in groundwater, the use of such water for irrigation can increase the levels of radioactive elements in the soil.

Mining operations, particularly those related to the extraction of uranium, thorium, and other radioactive minerals, can release significant amounts of NORMs into the surrounding environment. Mining activities can lead to the direct contamination of agricultural soils, particularly in regions where open-pit mining exposes large amounts of uranium-rich ores to the surface. Additionally, the tailings produced by mining operations can contain high concentrations of NORMs and can contribute to the spread of these materials through wind, water, and human activities.

The extraction of oil and gas from underground reservoirs can release NORMs, especially radium and radon, into the environment. In certain areas, oil and gas extraction can bring to the surface underground brines that contain elevated levels of NORMs. These materials can then accumulate in soils near extraction sites, where they can affect agricultural productivity and food safety.

Coal is a natural source of uranium, thorium, and other radioactive elements, and the combustion of coal for energy production can release these materials into the atmosphere, water, and soil. Coal ash, a byproduct of burning coal, contains concentrated levels of NORMs and is often disposed of in landfills or used in construction materials, potentially leading to the contamination of agricultural soils.

2.6.2 Uptake Mechanisms of NORMs by Food Crops

Food crops take up NORMs through their root systems, where they absorb water and nutrients from the soil. The primary mechanism for the uptake of NORMs in plants is through the root system. Roots absorb water from the soil, and with this water, trace elements and contaminants, including NORMs, can be absorbed. The ability of a plant to absorb NORMs depends on the chemical form of the radioactive material, the solubility of the material, and the ion-exchange capacity of the soil. For example, soluble forms of uranium and radium are more readily absorbed by plant roots compared to insoluble forms, which are less bioavailable.

Many NORMs, particularly uranium and radium, exist in the soil in ionic form, and plant roots can uptake these ions via ion exchange processes. In this process, ions such as calcium, potassium, or magnesium in the soil are exchanged for radioactive ions such as uranium or radium. This mechanism is particularly important in soils with high concentrations of calcium or other cations that can readily exchange with NORMs.

Uranium and thorium can mimic phosphorus in the soil due to their similar chemical properties. Plants often take up uranium in place of phosphorus, especially in soils with low phosphorus availability. This competitive uptake mechanism is a key pathway for uranium absorption by plants, as uranium often binds to phosphate ions in the soil. Crops growing in phosphorus-deficient soils are more likely to accumulate higher levels of uranium due to this competition.

Radon, being a gas, does not enter the plant through the roots directly. Instead, radon is released from the soil as a gas and may be absorbed by plants through diffusion from the soil into the atmosphere. Once in the atmosphere, radon can be absorbed by plant leaves through the stomata or by the root system in the case of radon dissolved in water. Radon is known to accumulate more readily in certain parts of plants, particularly in the leaves.

After uptake through the roots, NORMs are translocated within the plant to different tissues. In many cases, the movement of these radioactive elements through the plant follows the general nutrient transport pathways. For example, uranium can be transported via the xylem, the plant’s vascular tissue responsible for water and nutrient transport. From the roots, uranium may move upward through the plant to the stems, leaves, and reproductive organs.

Radium and thorium also follow similar translocation pathways in plants. However, the amount of NORM translocated to the edible parts of plants varies depending on the plant species, growth conditions, and the chemical form of the NORMs. The accumulation of NORMs in plant tissues is highly dependent on soil factors, such as pH, organic matter content, and soil texture. For instance, acidic soils can increase the solubility of uranium, making it more bioavailable for uptake by plants. Additionally, the plant's metabolic activity and nutrient requirements influence the accumulation of NORMs. Some plants, especially those that are hyperaccumulators, may concentrate certain elements at higher levels than others. Radium, for example, tends to accumulate in the roots and stems of some plants, whereas uranium may accumulate more readily in the leaves.

2.6.2.3 **Factors Affecting NORM Uptake by Crops**

Several environmental and soil factors influence the uptake of NORMs by food crops. These factors include soil properties, crop type, and environmental conditions, all of which can enhance or inhibit the absorption of radioactive materials by plants. The pH of the soil affects the solubility and mobility of NORMs. Acidic soils tend to increase the solubility of uranium and thorium, thereby enhancing their uptake by plants. On the other hand, alkaline soils can decrease the bioavailability of certain NORMs, especially radium.

The organic content of the soil can bind to radioactive elements, reducing their availability to plants. Soils rich in organic matter can have lower concentrations of bioavailable NORMs, as organic compounds can form stable complexes with these materials, decreasing their mobility and uptake by plants. The presence of water in the soil also plays a crucial role in the uptake of NORMs by plants. Irrigated crops are at a higher risk of accumulating NORMs, particularly when the water source is contaminated with uranium or radium.

Different plant species exhibit varying levels of sensitivity to NORMs. Some species are better at absorbing and translocating these materials than others, depending on their root architecture, metabolic processes, and ion transport mechanisms. For instance, certain crops, such as leafy vegetables, may accumulate higher levels of radium and uranium than root crops, which are more likely to accumulate NORMs in their roots.

2.7 Food Crops as Vectors for PTEs and NORMs

2.7.1 Bioaccumulation and Biomagnification in Cassava, Cocoyam, and Yam

Bioaccumulation and biomagnification are processes through which potentially toxic elements (PTEs) and pollutants accumulate in the tissues of living organisms over time. Bioaccumulation refers to the build-up of substances, such as heavy metals and pesticides, within an individual organism, while biomagnification describes the increasing concentration of these substances as they move up the food chain. These processes are significant concerns in agricultural systems, especially in areas where soils are contaminated with potentially toxic elements (PTEs), as they can lead to the contamination of food crops. Cassava, cocoyam, and yam are staple crops in many tropical regions, including West Africa, where they are essential for food security. However, their ability to accumulate PTEs from contaminated soils may pose health risks to humans and animals that consume them. This essay explores the bioaccumulation and biomagnification of PTEs in cassava, cocoyam, and yam, examining the mechanisms involved, the factors influencing accumulation, and the potential implications for human health.

2.7.2 Mechanisms of Bioaccumulation

The bioaccumulation of PTEs in cassava, cocoyam, and yam is influenced by several physiological and environmental factors. These include the chemical form of the contaminants, soil properties, and plant-specific factors such as root architecture, nutrient uptake, and metabolic processes.

Potentially toxic elements in the soil can exist in various chemical forms, including organic and inorganic compounds. The bioavailability of these forms determines their uptake by plants. Water-soluble forms of PTEs, such as cadmium nitrate, are more easily absorbed by plant roots than insoluble forms. Additionally, the presence of other soil elements, such as calcium and potassium, can affect the uptake of toxic metals through ion-exchange processes in plant roots.

Soil pH significantly impacts the bioavailability of PTEs. Acidic soils often increase the solubility of heavy metals, making them more available for absorption by plant roots. In contrast, alkaline soils can reduce the bioavailability of certain toxic elements, limiting their uptake by plants.

The root system of a plant plays a crucial role in the uptake of PTEs. Roots with a larger surface area, such as those of cassava, may absorb higher amounts of contaminants from the soil. Additionally, the plant’s nutrient uptake processes can influence the absorption of PTEs. For instance, plants with a high demand for nutrients like calcium or phosphorus may inadvertently take up more heavy metals, as these elements compete for similar absorption pathways in the roots.

Organic matter in soil can bind to toxic elements, potentially reducing their bioavailability. High organic matter content can lead to the formation of complexes between metals and organic compounds, making it more difficult for plants to absorb these elements. On the other hand, organic-rich soils may also promote the leaching of contaminants from the soil, increasing the availability of toxic elements to plants.

2.7.3 Biomagnification of PTEs in the Food Chain

Biomagnification occurs when the concentration of PTEs increases as they move up the food chain, from primary producers (plants) to herbivores, and eventually to humans or higher-level carnivores. This process is of particular concern in agricultural systems where contaminated crops serve as the base of the food chain. When cassava, cocoyam, and yam absorb PTEs from the soil, they can serve as a source of contamination for herbivores, including livestock and humans. The concentration of contaminants in the edible parts of these crops, particularly tubers and roots, can vary depending on factors such as plant species, soil contamination levels, and climate conditions.

Herbivores that consume contaminated cassava, cocoyam, and yam may accumulate higher levels of PTEs in their bodies, as these elements are not easily excreted. For example, animals that feed on contaminated plants may experience bioaccumulation in their tissues, which can lead to higher concentrations of PTEs in the food chain. This biomagnification effect can be particularly problematic for humans who consume contaminated livestock products.

The biomagnification of PTEs through the food chain can result in significant health risks for humans. For example, the consumption of cassava, cocoyam, or yam that has accumulated toxic metals like arsenic, cadmium, or lead may lead to chronic health issues such as kidney damage, neurological disorders, and cancer. The effects of long-term exposure to low levels of these contaminants are still under study, but the potential risks to public health are substantial, especially in areas with high levels of soil contamination.

2.8 Human and Ecological Health Risks from PTEs and NORMs

2.8.1 Human Health Risks from PTEs and NORMs

The presence of potentially toxic elements (PTEs) and naturally occurring radioactive materials (NORMs) in the environment is a growing concern due to their detrimental impacts on both human health and ecological systems. PTEs, which include heavy metals like arsenic, lead, cadmium, and mercury, and NORMs such as radium, uranium, and thorium, are pervasive pollutants in soils, water, and food crops. These elements can enter the environment through natural processes, human activities, or a combination of both. Once released, they can persist in the environment for extended periods, leading to accumulation in organisms and subsequent ecological and human health risks.

Human health risks from PTEs and NORMs arise from exposure through direct contact with contaminated soil, ingestion of contaminated food and water, or inhalation of dust or airborne particles. Long-term exposure to these elements, even at low concentrations, can result in severe health problems, including cancer, neurological disorders, kidney damage, and reproductive issues.

Heavy metals such as cadmium, lead, and mercury are known to be highly toxic to humans. Chronic exposure to cadmium, for instance, is linked to kidney damage, lung cancer, and bone diseases (Ghane et al., 2022). Lead exposure can lead to cognitive impairments, particularly in children, and can also cause cardiovascular and kidney damage. Mercury, another highly toxic metal, has been associated with neurological and developmental disorders, especially in foetuses and young children (Ghane et al., 2022). Exposure to NORMs, particularly radon gas, poses significant health risks. Radon is a carcinogen that, when inhaled, can lead to lung cancer. In regions with high concentrations of uranium in the soil, the decay of uranium into radon gas can lead to elevated indoor radon levels, increasing the risk of lung cancer for people living in these areas (Bersimbaev & Bulgakova, 2015). Prolonged exposure to high levels of other NORMs like thorium and radium can also lead to bone cancer and leukaemia, primarily through the ingestion of contaminated water or food.

Both PTEs and NORMs can accumulate in organisms over time, leading to bioaccumulation. For example, heavy metals taken up by plants can then be transferred to herbivores that consume them, and from there to higher-level consumers, including humans. The concentration of toxic elements increases as they move up the food chain in a process called biomagnification. This can lead to significantly higher levels of PTEs and NORMs in top predators, including humans, with severe health consequences.

2.8.2 Ecological Health Risks from PTEs and NORMs

Ecological systems are also vulnerable to the toxic effects of PTEs and NORMs. These pollutants can harm ecosystems by contaminating soils, water, and air, leading to a reduction in biodiversity, disruption of food webs, and degradation of habitat quality. PTEs and NORMs present in contaminated soils and water can negatively affect plant growth and the organisms that rely on these habitats. For example, high concentrations of cadmium in the soil can inhibit plant growth and reduce agricultural productivity.

Toxic metals such as lead and mercury can also accumulate in aquatic ecosystems, leading to the poisoning of aquatic organisms like fish and amphibians, which are unable to metabolize or eliminate these substances effectively (Kolarova & Napiórkowski, 2021).

Wildlife species that inhabit contaminated environments may experience a range of health issues due to the bioaccumulation of PTEs and NORMs in their bodies. Animals higher up the food chain, such as birds of prey or carnivorous mammals, are particularly at risk due to biomagnification. In aquatic environments, fish that accumulate high concentrations of mercury or cadmium may suffer from impaired reproductive success, weakened immune systems, and increased mortality rates (Y. Liu et al., 2022).

Long-term exposure to PTEs and NORMs can reduce biodiversity by causing the decline or extinction of sensitive species. Plants and animals that cannot adapt to the presence of toxic elements may either die or migrate, leaving behind a less diverse ecosystem. This loss of biodiversity can disrupt ecosystem services such as pollination, water purification, and soil fertility.

2.8.2.1 Toxicological Impacts of PTEs on Human Health

Potentially toxic elements (PTEs), often referred to as heavy metals, include a group of elements that possess toxic properties when they accumulate in biological systems. These elements, which include cadmium, arsenic, lead, mercury, and chromium, are of great concern due to their widespread presence in the environment and their potential to adversely affect human health. PTEs can enter the human body through various pathways, including ingestion of contaminated food and water, inhalation of polluted air, and dermal absorption. Once inside the body, these elements can cause a wide range of acute and chronic health effects, some of which may lead to irreversible damage. PTEs exhibit toxicity through various mechanisms that disrupt normal biological functions. One of the primary ways that PTEs cause harm is by interfering with cellular processes, enzymes, and organ systems. The toxicity of these elements depends on several factors, including their chemical form, dose, route of exposure, and the duration of exposure.

Many PTEs induce oxidative stress in the human body. Oxidative stress occurs when there is an imbalance between the production of reactive oxygen species (ROS) and the body's ability to detoxify them using antioxidants. This results in cellular damage, including lipid peroxidation, DNA damage, and protein oxidation, which can lead to inflammation, organ damage, and carcinogenesis. For instance, arsenic and cadmium are well-known to induce oxidative stress, contributing to their toxicity (Zwolak, 2020).
PTEs can interfere with the function of enzymes by binding to active sites or disrupting their structure. This disruption can impair important biochemical processes in the body, such as energy production, metabolism, and detoxification. Lead, for example, inhibits enzymes involved in heme synthesis, which can lead to anaemia and neurological impairments (Słota et al., 2022).

Some PTEs, such as mercury and cadmium, interfere with cellular signalling pathways that regulate cell growth, apoptosis, and immune responses. By disrupting these pathways, these metals can promote the development of cancer, autoimmune diseases, and other chronic health conditions (Popov Aleksandrov et al., 2021).

2.4.2.2 Health Effects of PTEs

The toxicological impacts of PTEs on human health vary depending on the specific element involved and the level of exposure. Chronic exposure to cadmium, often through contaminated food, water, or occupational environments, can lead to kidney damage, lung disease, and bone weakening (osteomalacia and osteoporosis). Cadmium is also classified as a carcinogen, and long-term exposure has been linked to an increased risk of lung and prostate cancer (Genchi et al., 2020). Cadmium exposure can also cause cardiovascular disease by affecting blood pressure and the structure of blood vessels (Genchi et al., 2020).

Arsenic is a well-known carcinogen that poses a significant risk to human health. Long-term exposure to arsenic, primarily through drinking water contaminated with arsenic, has been associated with skin, lung, bladder, and liver cancers. It can also cause non-cancerous effects such as cardiovascular disease, diabetes, and developmental defects (K. M. Khan et al., 2020). Arsenic exposure is particularly dangerous to vulnerable populations, including pregnant women and children.

Lead exposure has been linked to a wide range of health problems, particularly in children. Lead poisoning can cause developmental delays, cognitive impairments, and behavioural problems in children. In adults, long-term exposure to lead can result in hypertension, kidney damage, and neurological disorders. Lead also affects the hematologic system, causing anaemia and interfering with red blood cell production (Ugwuja et al., 2020).

Mercury exposure, especially in the form of methylmercury, is highly toxic to the nervous system. Chronic exposure to mercury can cause neurological disorders such as tremors, memory loss, and cognitive impairments. Methylmercury is particularly harmful during foetal development and can cause developmental delays, sensory impairment, and motor dysfunction in infants (Al-Saleh et al., 2020). In addition to neurological effects, mercury exposure can damage the kidneys and the immune system.

Chromium exists in several forms, with hexavalent chromium (Cr(VI)) being the most toxic. Long-term exposure to Cr(VI) has been linked to lung cancer, respiratory problems, and skin ulcers. Cr(VI) is also a strong irritant to the gastrointestinal tract, causing nausea, vomiting, and abdominal pain when ingested. Chromium exposure is also associated with liver and kidney damage (Chakraborty et al., 2022).

2.8.2.3 Factors Influencing the Toxicity of PTEs

The amount of the toxic element and the duration of exposure are crucial in determining the degree of toxicity. Low-level, chronic exposure may result in cumulative effects that develop over time, while high-level, acute exposure may cause immediate and severe health consequences. For example, acute lead poisoning may cause seizures and coma, while chronic exposure may lead to developmental deficits in children (Stevanin, 2019). The route through which PTEs enter the body significantly affects their toxic effects. Ingestion of contaminated water or food is a common route of exposure to arsenic, cadmium, and lead, whereas inhalation of contaminated air or dust is a major route for mercury and chromium exposure in occupational settings (WHO, 2021). Dermal absorption of certain metals, such as chromium, can also cause localized toxicity.

Age, gender, genetics, and pre-existing health conditions can influence how individuals respond to PTE exposure. Children, for example, are more susceptible to the harmful effects of lead and mercury due to their developing nervous systems (Anyimah-Ackah et al., 2019). Similarly, individuals with compromised renal function may be more vulnerable to the toxic effects of cadmium and mercury.

2.8.3 Radiological Impacts of NORMs on Human Health

Naturally Occurring Radioactive Materials (NORMs) refer to radioactive substances that are found in the environment without human intervention. These materials, including elements like uranium, thorium, and radium, are naturally present in the Earth's crust, water, and air. While these elements are part of the natural radiation environment, they can pose significant health risks when they accumulate in significant quantities, especially in areas with high concentrations of NORMs, such as mining regions. The radiological impacts of NORMs on human health are a cause for concern due to their ability to emit ionizing radiation(Foy & Bosman, 2021), which can cause biological damage at the cellular level. This essay discusses the radiological impacts of NORMs on human health, including the mechanisms of radiation exposure, the health effects, and the factors that influence the severity of exposure.

2.8.3.1 Mechanisms of Radiation Exposure from NORMs

NORMs emit ionizing radiation, which has enough energy to remove electrons from atoms, leading to the creation of charged particles called ions (Rika Widianita, 2023). This process, known as ionization, can damage or alter the structure of molecules, including DNA, proteins, and lipids. There are three primary types of radiation emitted by NORMs: alpha (α) particles, beta (β) particles, and gamma (γ) rays. Each type of radiation has different penetration abilities and poses distinct risks to human health.

- **Alpha Particles**: Alpha radiation consists of large, heavy particles that are emitted from the decay of elements like uranium and radium. Although alpha particles are relatively low in energy and cannot penetrate the skin, they can cause significant biological damage if inhaled, ingested, or absorbed into the body. Inside the body, alpha particles can cause ionization of cells, leading to tissue damage, mutations, and cancer (UNSCEAR, 2000a).
- **Beta Particles**: Beta radiation consists of high-energy electrons emitted during the decay of certain radioactive isotopes such as thorium and radium. Beta particles have greater penetrating power than alpha particles, and while they can penetrate the outer layer of skin, they pose a greater risk when inhaled or ingested. Inside the body, beta particles can affect tissues and organs, leading to burns, organ damage, and cancer (Ozturk et al., 2022).
- **Gamma Rays**: Gamma radiation is a form of electromagnetic radiation, similar to X-rays but with higher energy. Gamma rays can penetrate deep into tissues and organs, posing significant health risks even when exposure is external. Gamma radiation is typically associated with the decay of isotopes such as radium, uranium, and thorium. It can lead to cellular damage, including DNA mutations, which may result in cancer and other health issues(Adeola et al., 2023) .

2.8.3.2 Health Effects of NORM Exposure

The health effects of NORM exposure depend on the type of radiation, the amount of exposure, and the duration of exposure. Ionizing radiation from NORMs can cause both stochastic (random) and deterministic (predictable) health effects. Stochastic effects, such as cancer, are the result of random mutations in DNA caused by radiation, while deterministic effects, such as radiation burns or tissue damage, occur only after a certain threshold of exposure is reached.

- **Cancer**: One of the most significant health risks associated with NORM exposure is an increased risk of cancer. Ionizing radiation can cause DNA damage, leading to mutations that may result in the development of tumours. Studies have shown that exposure to NORMs, particularly radon and uranium, is linked to an increased risk of lung cancer, as inhaled radon and its progeny can damage lung tissue (Hodgson et al., 2015). Prolonged exposure to high levels of radium has also been associated with bone cancer, leukaemia, and other cancers (UNSCEAR, 2000a).
- **Respiratory Issues**: Radon, a radioactive gas that emanates from the decay of uranium and thorium, poses a significant health risk, particularly in confined spaces like homes and underground mines. Prolonged inhalation of radon and its radioactive progeny can damage lung tissues and increase the risk of respiratory diseases, including lung cancer. According to the World Health Organization (WHO), radon exposure is the second leading cause of lung cancer after smoking (WHO, 2004).
- **Bone and Liver Damage**: Radium, another common NORM, tends to accumulate in bones due to its chemical similarity to calcium. Once in the bone, radium can emit alpha particles that cause localized damage to bone tissue, leading to bone cancers such as osteosarcoma. Additionally, radium can accumulate in the liver and other organs, causing damage to tissues and increasing the risk of cancer (Grzywa-Celińska et al., 2020).
- **Kidney Damage**: Uranium exposure, particularly in mining and processing environments, has been linked to kidney damage. Uranium compounds, when ingested or inhaled, can accumulate in the kidneys and cause nephrotoxicity, which

may lead to renal failure. The chemical toxicity of uranium, combined with its radiological effects, can significantly affect kidney function (Guéguen & Frerejacques, 2022).

- **Genetic and Developmental Effects**: Exposure to NORMs, particularly during pregnancy, can have harmful effects on foetal development. Ionizing radiation can cause genetic mutations in developing cells, leading to birth defects, developmental delays, and an increased risk of childhood cancers. Pregnant women exposed to radon or other NORMs are at an increased risk of delivering babies with low birth weight, birth defects, and developmental disorders (UNSCEAR, 2019).

2.8.3.3 Factors Influencing the Radiological Health Risks of NORMs

Several factors can influence the level of health risk associated with NORM exposure. These include the type of NORM involved, the duration and intensity of exposure, and the route of exposure.

- **Type of NORM**: Different NORMs emit different types of radiation and have varying levels of toxicity. For example, radon, uranium, and thorium emit alpha particles, while radium can emit both alpha and gamma radiation. The presence of gamma radiation increases the risk of deep tissue damage compared to alpha radiation, which is primarily a concern when inhaled or ingested.
- **Exposure Duration and Intensity**: The longer the exposure and the higher the intensity of radiation, the greater the risk of adverse health effects. Occupational exposure to NORMs, such as in uranium mining or radon-exposed environments, increases the likelihood of cancer and other health effects. The cumulative nature of radiation exposure means that even low levels of exposure over extended periods can result in significant health risks.

- **Route of Exposure**: The route through which NORMs enter the body significantly affects the type of health impact. Inhalation of radon gas, ingestion of contaminated water or food, and dermal contact with radioactive materials are all common pathways of exposure. Inhalation is particularly concerning for NORMs like radon and its progeny, as these materials can accumulate in the lungs and lead to respiratory diseases (WHO, 2009).
- **Vulnerable Populations**: Certain populations, such as children, pregnant women, and individuals with pre-existing health conditions, are more vulnerable to the effects of NORM exposure. Children are more sensitive to radiation because their cells are dividing rapidly during development, making them more prone to genetic mutations. Pregnant women are particularly at risk as radiation exposure can lead to birth defects and developmental issues in the foetus (UNSCEAR, 2000b).

2.9 International Guidelines and Regulatory Agencies

Several international organizations provide guidance and set regulatory standards for PTEs and NORMs in agricultural soils and food crops. These include:

- **World Health Organization (WHO)**: WHO sets guidelines for the maximum allowable levels of PTEs and NORMs in drinking water, food, and air. WHO's International Programme on Chemical Safety (IPCS) provides extensive reports on the health risks associated with PTEs and NORMs, offering risk assessment frameworks for the regulation of these substances (WHO, 2004).
- **European Food Safety Authority (EFSA)**: EFSA provides scientific advice and risk assessments on the safety of food and feed in the European Union. It sets permissible limits for PTEs in food crops, particularly with regard to cadmium, arsenic, and lead, in accordance with the EU's food safety standards (EFSA, 2013).

- **International Atomic Energy Agency (IAEA)**: The IAEA provides guidelines for the safe handling of radioactive materials and establishes standards for radiation protection, particularly in areas with high concentrations of NORMs. It offers technical guidance on the measurement and assessment of radiation exposure in agricultural settings (IAEA, 2010).

2.9.1 National Regulatory Bodies

In addition to international standards, many countries have established their own regulations for PTEs and NORMs in agricultural soils and food crops. In the United States, the FDA, EPA, and the U.S. Department of Agriculture (USDA) play key roles in regulating the levels of these substances in food. Similarly, in the European Union, national authorities work in collaboration with EFSA to enforce food safety regulations and set limits on the concentration of PTEs in crops (EFSA, 2013).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

The Mampong Municipality is among the one hundred and nine municipalities in Ghana. It attained the status of a municipality in November 2007. It was created following the splitting and the upgrading of the former Sekyere West District into Mampong Municipal and Sekyere Central District by Legislative Instrument (L.I.1908). It is bounded to the south by Sekyere South District, to the east by Sekyere Central District, and to the north by Ejura Sekyeredumase Municipal (GSS, 2014). The major towns within the municipality are Mampong, Krobo, Dadease, Asaam, Kofiase, Adidwan, and Apaah. It has about 79 settlements, with about 61% of them being rural. The rural areas are mostly in the northern part of the municipality, where communities with an average of less than 50 people live in a dispersed pattern (GSS, 2014). The population of the municipality according to the 2021 population and housing census stands at 116,632, with 56,965 males and 59,667 females. The municipality is located within longitude 0005" W and 1030" and latitude 6055" N and 7030" N. The total land area covered by the municipality is 449 km^2 (GSS, 2014).

The Mampong municipality records an average annual rainfall of 1,270 mm and two rainy seasons. The major rainy season starts in March and ends in August, and the minor is between September and November. The remaining months span the harmattan dry season. The average temperature is 27 ºC with variations in mean monthly temperature ranging between 22 ºC and 30 ºC (Meteorological Service, Mampong, 2010).

The Mampong municipality lies within the wet semi-equatorial forest zone. Due to human activities like charcoal production, lumbering, and bushfires, the forest vegetation, particularly the northeastern part, has been reduced to savannah. Vegetation of primary origin can only be found within a reserve known as Kogyae (GSS, 2021).

Mampong is a major agricultural hub within the Ashanti Region, where subsistence and commercial farming of root and tuber crops like cassava, yam, and cocoyam are common (GSS, 2014). These crops are major dietary staples, making the area highly relevant for assessing human exposure through food. Additionally, the selection of Mampong allows for an ecological risk assessment in a typical Ghanaian agrarian ecosystem. Understanding the soil-to-crop transfer of contaminants in such an environment helps identify potential ecological impacts even in areas considered "clean." There is also limited research on radiological and chemical contamination in food crops and soils from Mampong. This study helps fill that gap and supports national and regional environmental health monitoring frameworks. Figure 1 illustrates the map of the study area, highlighting the various sampling locations.

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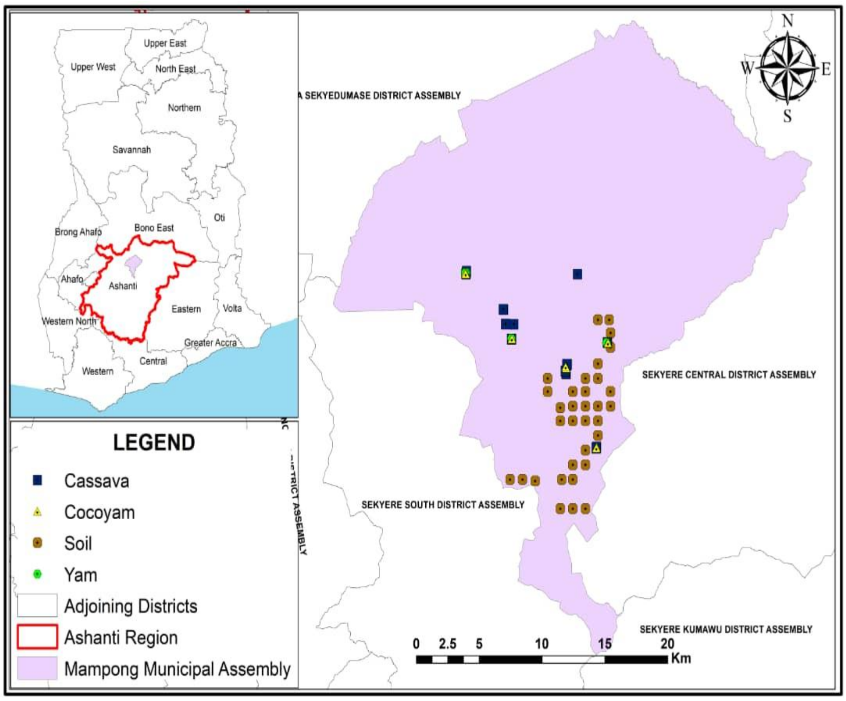

Figure 3.1: Map showing the communities sampled

3.2 Sample Collection and Preparation

Samples of soil and food crops were gathered from farmlands and residential neighbourhoods in Mampong Municipality using a systematic random sampling technique. A 1 km-by-1 km grid was created for the towns using a global positioning system program (GPS map, 64s Garmin, USA), and then samples were taken at the intersections. When surface soil sampling was hindered by obstructions like buildings or highways, the sampling sites were moved to the closest available places. Using sterile plastic hand shovels, after being collected at a depth of 0–15 cm, the soil samples were placed in Ziploc bags with clear labels. The food crop sample areas in the grids were specifically selected based on crop availability. Depending on sample availability, 194 samples comprising 117 soil samples and 77 food crop samples were collected from Mampong. The soil and food crop samples were air-dried at 110 °C to constant weight and homogenized using a mortar and pestle before being filtered through a 250 µm mesh standard testing sieve (ASTM E11, USA). Control samples were extracted from the Akenten Appiah-Menka University of Skills Training Entrepreneurial Development undisturbed forest and processed in the same way as regular samples to serve as a local environmental quality standard.

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3.3 Sample Analyses

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3.3.1 pH, and Electrical Conductivity

The Hanna H198127 combination meter for pH, EC, and TDS/temperature was used to test the samples' pH, electrical conductivity (EC), and total dissolved solids (TDS). The determination was made by mixing 20 g of the sieved soil sample with 40 mL of distilled water (i.e. 1:2 dried soil: distilled water). The combination was allowed to settle for an hour before the pH, EC, and TDS were determined from the supernatant (Islam et al., 2017).

3.3.2 Soil Organic Matter

The loss-on-ignition approach was used to determine the total organic carbon content of soil samples (Schumacher, 2002). Two grams of the soil were weighed directly into a crucible and then heated at 105 °C for two hours. The samples were removed and placed in a desiccator to cool to room temperature before being weighed. The samples were then heated in a muffle furnace to 550 °C for four hours. The samples were removed from the furnace and allowed to cool to ambient temperature in a desiccator before being weighed once again (Schumacher, 2002). Duplicate measurements were made to ensure that the outcomes could be replicated. By dividing the pre-ignition weight by the post-ignition weight and multiplying the result by 100, the quantity of organic matter was calculated.

3.3.3 Effective Cation Exchange Capacity

The effective cation exchange capacity was determined using the AFNOR NFX 31-108 Method. A 1 M ammonium acetate solution (about 75 mL) was percolated through 2.5 g of soil to saturate the exchange sites with ammonium. Excess reagent was removed using 25% ethyl alcohol. A flame photometer (model: FP902, PG instruments, UK) and an atomic absorption spectrophotometer (model: AAS500, PG instruments, UK) are used to quantify the elemental concentrations (exchanged ammonium). By deducting the total exchangeable acidity from the Al-induced exchangeable acidity using unbuffered KCl, the concentration of exchangeable protons in soil samples with a pH lower than 6.5 was calculated (Solly et al., 2020). Exchangeable proton concentrations were considered negligible in soil samples with a pH higher than 7. Lastly, the effective cation exchange capacity was calculated by adding the charge equivalents of exchangeable Na, K, Mg, Ca, Al, and H (Aprile & Lorandi, 2012).

3.4 Activity Concentration of the Radionuclides

With the aid of the High Purity Germanium detector (HPGe), direct instrumental analysis without pre-treatment (non-destructive) was utilized to quantify the gamma rays in the dust. The gamma spectrometry apparatus consists of a computer-based multichannel analyzer and an n-type HPGe detector. The detector's relative efficiency is 40% with a gamma ray energy of 1332 keV from ^{60}Co and an energy resolution of 2.0 keV. Radionuclides were recognized individually using their characteristic gamma-ray energy and then quantitatively examined using the Genie 2000 gamma capture and analysis program. To reduce background radiation, the detector is shielded with a 100 mm passive shielding composed of old lead lined with 3 mm of plexiglass, copper, and cadmium. The detector is cooled using liquid nitrogen at a temperature of around -196 °C (77 K). Ten empty Marinelli beakers were meticulously cleaned and counted for 36,000 seconds in the same geometry as the samples in order to ascertain the background distribution in the vicinity of the detector (quality control). The net peak area of the gamma rays of the observed isotopes was corrected using the background spectra. The detector's minimal detectable activity for ^{238}U (0.12 Bq/kg), ^{232}Th (0.11 Bq/kg), and ^{40}K (0.15 Bq/kg) was also ascertained using the background spectra.

3.4.1 Efficiency Calibration

In order to calibrate efficiency, a spectrum of the calibration standard was obtained until the count rate at the peak of total absorption was computed with a 95% confidence level and less than 1% statistical uncertainty. In order to calculate the efficiency at the moment of measurement, the net count rate was calculated at the photo peaks for each energy. To find the efficiencies at various peak energies given the measurement geometry utilized, the efficiency at each energy was plotted as a function of the peak energy and extrapolated, as seen in Figure 3.2.

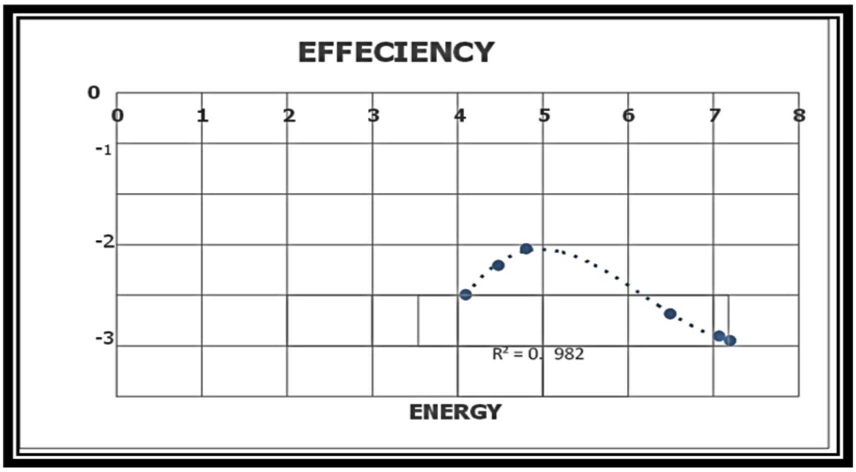

Figure 3.2: Efficiency Curve for Calibrating High Purity Germanium Detector

3.4.2 Calculation of Activity Concentration and Estimation of Doses

The daughter products were used to assess the activity concentration of the ^{238}U, ^{232}Th and ^{40}K. The weighted average activity at each peak in the spectrum was used to determine the activity concentration for a nuclide with several peaks. The activity of ^{238}U was calculated using the emissions of ^{214}Bi (609.31, 1120.29, 1764.49 keV) and ^{214}Pb (295.22, 351.93 keV). The activity of ^{232}Th was assessed using the gamma emission lines of ^{212}Bi (727.33 keV), ^{228}Ac (209.25, 409.46, 463.0, 794.95, 911.20, 964.77, 968.97 keV), and ^{212}Pb (238.63, 300.09 keV). Its only γ-ray line of peak energy, 1460.82 keV, was used to calculate ^{40}K. An empty Marinelli beaker was used to assess the background prior to sample measurement, using the same measurement parameters as the samples. The time count was 72,000s. The Genie 2000 V3.3 was used for data collection, presentation, and online spectrum analysis.

Canberra-based spectroscopic software. Using Equation 3.1, the activity concentration (AC) (Bq/kg) of each radionuclide in a sample was determined from the spectrum.

$$A_C\,(^{238}U,\ ^{232}Th,\ ^{40}K) = \frac{Nsam}{?(?\times\eta(E)\times Tc\times Msam)} \qquad (3.1)$$

Where P(E) is the gamma emission probability, Tc (s) is the counting time in seconds, Msam (kg) is the sample's mass, Nsam (cps) is its net peak area inside the peak range, and (E) is the photo peak efficiency that was measured using the standard solution (Otoo et al., 2018a).

3.4.3 Radium Equivalent Activity (Ra_{eq})

Radium equivalent activity has been developed as a single radiological measure that compares the particular activity of materials with varying amounts of ^{238}U, ^{232}Th, and ^{40}K, since the distribution of radionuclides in soil and sediment is not uniform (Isinkaye & Emelue, 2015). To eliminate this non-uniformity and evaluate the possible radiation linked to radiation hazards, the Ra_{eq} index has been widely used (Abedin & Khan, 2022a).. Equation 3.2 is used to determine the Ra_{eq};

$$Ra_{eq}\ (Bq/kg) = A_u + 1.43 \text{ x } A_{Th} + 0.077 \text{ x } A_K \qquad (3.2)$$

where the particular activity of ^{226}Ra, ^{232}Th, and ^{40}K in Bq/kg are represented by A_u, A_{Th}, and A_K, respectively (UNSCEAR, 2000; Shuaibu et al., 2017; Addo et al., 2020). It was defined with the assumption that 370 Bq/kg of ^{238}U, 259 Bq/kg of ^{232}Th, and 4810 Bq/kg of ^{40}K would all yield the same gamma-ray dosage equivalent equivalent (Otoo et al., 2018b; UNSCEAR, 2022b). Ra_{eq} was given a maximum permissible limit of 370 Bq/kg in order to account for possible radiological health safety (Abedin & Khan, 2022b).

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3.4.4 External Hazard Index (H_{ex}) and Internal Hazard Index (H_{in})

The external hazard index is a measure used to calculate the pace at which soil radiation exposure occurs in the human body. The highest limit of Ra_{eq} (370 Bq/kg) and the maximum annual radiation exposure (1.5 mSv/y) are represented by the maximum value of H_{ex} equal to unity. Equation 3.3 was used to obtain the external hazard index Hex: (Otoo et al., 2018; Shayeb & Baloch, 2020; Traoré et al., 2019; Tuo et al., 2020).

$$H_{ex} = \frac{A_u}{370} + \frac{A_{Th}}{259} + \frac{A_k}{4810} \leq 1 \qquad (3.3)$$

where the activity concentrations (Bq/kg) of ^{238}U, ^{232}Th, and ^{40}K in soil samples are represented by A_u, A_{Th}, and A, respectively. Radon and its byproducts are radioactively hazardous to the respiratory system in addition to the external danger index (Isinkaye & Emelue, 2015).

To assess these risks, an internal hazard index (H_{in}) was computed using Equation 3.4 (Traoré et al., 2019; Tuo et al., 2020).

$$H_{in} = \frac{A_U}{370} + \frac{A_{Th}}{259} + \frac{A_k}{4810} \leq 1 \qquad (3.4)$$

Where A_u, A_{Th}, and A_K are the activity concentrations (Bq/kg) of ^{238}U, ^{232}Th and ^{40}K in soil samples, respectively.

3.4.5 Absorbed dose rate (ADR)

The absorbed dose rate (ADR) in the air (outside) at 1 m above ground level is the amount of radiation that a human receives as a result of the gamma rays generated by the radionuclides (^{238}U, ^{232}Th, and ^{40}K) present in soil samples. This is based on the conversion coefficients given in UNSCEAR (2000) and the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in soil samples (ADR) in the ambient air (Shayeb & Baloch, 2020b). According to ((UNSCEAR, 2000b), the conversion factors are 0.0417 nGy/h per Bq/kg for

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^{40}K, 0.604 nGy/h per Bq/kg for ^{232}Th, and 0.462 nGy/h per Bq/kg for ^{238}U. Equation 3.5 can be used to estimate it.

$$\text{AGDR (nGy/}h\text{)} = 0.462 \text{ x } A_{\mathrm{U}} + 0.604 \text{ x } A_{\mathrm{Th}} + 0.0417 \text{ x } A_{\mathrm{K}} \qquad (3.5)$$

Where A_U, A_{Th} and A_K carry their usual meanings.

3.4.6 Annual Effective Dose Equivalent (AEDE)

The dose conversion factor calculated from the absorbed gamma radiation rate in the air to the effective dose equivalent received by an adult was used to estimate the annual effective dose equivalent (AEDE) for the outdoor environment. According to UNSCEAR, Equation 3.6 is used to determine the population's yearly effective dose rate (UNSCEAR, 2000).

$$\text{AEDE (mSv/y)} = \text{AGDR} \times 8760 \times 0.2 \times 0.7 \times 10^{-6} \qquad \textit{(Equation 3.6)}$$

where 0.7 is the dose conversion factor (in a unit of SvGy-1) for environmental exposure to moderately energetic gamma rays, 0.2 is the outdoor occupancy factor (OF), and 8760 is the total number of hours per year (Shayeb & Baloch, 2020b).

3.4.7 Gamma representative level index (Iγ)

Iγ may be computed using Equation 3.7 to determine the degree of natural radiation risk from dust samples associated with gamma (γ) emitters (Abedin & Khan, 2022a)

$$\mathrm{I}\gamma = \frac{A_u}{150} + \frac{A_{Th}}{100} + \frac{A_K}{1500} \qquad (3.7)$$

3.4.8 Excess Lifetime Cancer Risk (ELCR)

Radioactivity in building materials is known to cause cancer because it accumulates radon and its progeny in indoor air that comes from a room's wall and floor(Isinkaye & Emelue, 2015). The chance of developing excess cancer as a result of radiation exposure to radioactive materials over the course of a lifetime at a certain exposure level is known as excess lifetime cancer risk, or ELCR (Otoo et al., 2018). Equation 3.8 was used to calculate ELCR:

$$\text{ELCR} = \text{AEDE} \times \text{DL} \times \text{RF} \qquad (3.8)$$

DL is the average life expectancy (estimated to be 70 years), AEDE is the annual effective dose equivalent, and RF is the risk factor, or the fatal cancer risk per sievert. Analysis of NIST 2711a and NIST 1575a standard reference materials (SRM), process blanks, and recovery tests were conducted during the XRF runs to guarantee the analytical method's dependability. The ICRP adopts RF as 0.05 for the general population (ICRP 60, 1990). Standard reference materials (NIST 2711a) and NIST 1575a yielded average recoveries that were consistently more than 75 ± 5%. Reproducibility studies using nine replicate samples showed acceptable reproducibility with an average relative percentage variation of 23% for As, 10% for Cr, 8.5% for Cu, 9.5% for Ni, 12% for Pb, and 7.9% for Zn (Dodd et al. 2023).

3.5 Total Metal Concentration Analysis

A Niton XL3t GOLD field portable X-ray fluorescence (FP-XRF) spectrometer was used to analyze the heavy metals in the food crop and sieved soil samples (USEPA, 2003). An inductively coupled plasma-mass spectrometer (ICP-MS) was then used to corroborate the findings. To put it briefly, a small (~ 30 mm) polyethylene container covered with propylene film had a portion of the sieved material filled three-quarters of the way to the

Commented [GD8]: For all the major instruments and equipment, indicate the manufacturer/brand, the model and the country of origin top. It was then placed within the instrument shroud and scanned for 180 seconds (USEPA, 2003).

Analysis of NIST 2711a and NIST 1575a standard reference materials (SRM), procedure blanks and recovery test were done during the XRF runs to ensure reliability of the analytical method. Average recoveries obtained by running standard reference materials (NIST 2711a) and (NIST 1575a) were consistently higher than 75±5%. A satisfactory level of reproducibility was demonstrated by the average relative percent difference of 23% for As, 10% for Cr, 8.5% for Cu, 9.5% for Ni, 12% for Pb, and 7.9% for Zn, as determined by reproducibility tests involving nine replicate samples (Dodd et al. 2023). The method detection limits which were computed as 3 times the standard deviation of the blank readings ranged widely between the metals as Pb < 2.7, As < 2.3, Zn < 9.0, Cu < 8.0, Ni < 7.0, Mn < 15, Cr < 4.6 and Cd < 2.9.

3.6 Estimation of Level of Contamination

By comparing site-specific data to background reference data or by utilizing pollution indices and enrichment factors, the degree of metal contamination was evaluated. The indices of pollution load, contamination factor, geo-accumulation index, and possible ecological danger were employed.

3.6.1 Geo-accumulation Index (Igeo)

The degree of elements contamination in the soil was assessed using the geo-accumulation index (Igeo). It was calculated using Equation 3.9.

$$Igeo = \log_2 \frac{Cn}{1.5Bn} \qquad 3.9$$

Where:

The elemental component of the soil is Cn. Bn = geochemical background concentration. Factor 1.5 accounts for potential variations in baseline values brought on by lithogenic factors. The seven values (0–6) on the index of geo-accumulation, or Igeo, scale range from zero contamination to extreme pollution Igeo is classified into seven descriptive classes as follows: < 0 = practically uncontaminated; 0 < Igeo ≤ 1 indicates uncontaminated to moderately contaminated state,1 < Igeo ≤ 2 indicates moderately contaminated state, 2 ≤ Igeo ≤ 3 indicates moderately to heavily contaminated state, 3 < Igeo ≤ 4 indicates heavily contaminated, 4 < Igeo ≤ 5 indicates heavily to extremely contaminated state. The Bn values of the metals were As 6.5, Cd 0.52, Co 4.3, Hg 0.06, Ni 4.2, Pb 31, and Cr 58.4 4 (Akanchise et al., 2020).

3.6.2 Contamination factor (Cf)

The level of metal contamination was assessed using the contamination factor (CF), which is the ratio of a metal's concentration in soil to background values. The CF was calculated using Equation 3.10 (Ekere et al., 2020).

$$\mathrm{CF} = \frac{Cm}{Ccrustal} \qquad 3.10$$

where Chm is the concentration of the heavy metal in the sample, CF is the heavy metal contamination factor, and C_{crusta}l is the concentration of the heavy metal in the continental crustal average/baseline concentration (Darko et al., 2017). The concentration factor, or CF, has four values (0–3, low to high CF). The CF is classified into four descriptive classes as follows: CF < 1 indicates low contamination, 1 ≤ CF < 3 indicates moderate contamination, 3 ≤ CF < 6 indicates considerable contamination, and CF ≥ 6 indicates very high contamination.

3.6.3 Pollution Load Index

Equation 3.11 demonstrates that the pollution load index (PLI), which represents the overall pollution status of the samples, is calculated using the n-root of the metals' CFs.

$$PLI=(CF1 \times CF2 \times CF3 \times \ldots\ldots..CFn)^{1/n} \qquad (3.11)$$

Where: CF = contamination factor of metal; n = number of metals studied.

Samples are categorized as unpolluted (PLI < 1), moderately contaminated (PLI = 1–3), highly polluted (PLI = 3–5), or very highly polluted (PLI > 5) based on their PLI values, according to (Akanchise et al., 2020)

3.6.4 Potential Ecological Risk

The PERI, or potential ecological risk index, which considers both the level of metal toxicity (CF) and the environment's reaction (TrF) to the pollutant, was used to assess the extent of elemental contamination in soils. Equations 3.12, 3.13 and 3.14 were used to determine the PERI, which is the total of the individual risk indices (RI).

$$F_i = C^i_n / C^i_o \qquad (3.12)$$

$E^i_r = T^i_r \times F_i$ (Olayinka-olagunju, 2022) (3.13)

$$RI = \sum E^i_r \qquad (3.14)$$

where F_i = metal pollution index

C^i_n = metal concentration in the sample

C^i_o = metal reference value

E^i_r = factor of monomial potential ecological risk

T^i_r = toxic response factor of metal (Hakanson 1980)

T^i_r is the metal's toxic response factor, F_i is the contamination factor, and *i* is the number of metals under study. The metals' hazardous response factors are Zn = 1, Cr = 2, Co = Cu = Pb = 5, Ni = 6, As = 10, Cd = 30, and Hg = 40 (Dash et al., 2021). Low risk (≤ 40), moderate risk (40 ≤ PERI ≤ 80), considerable risk (80 ≤ PERI ≤ 160), severe risk (160 ≤

PERI ≤ 320), and extremely high risk (PERI ≥ 320) are the categories into which PERI is divided.

3.6.5 Bioaccumulation Factor

The bioconcentration factor (BCF) indicates the ratio of elemental concentration in the plant part and the elemental concentration in the soil. BCF value ≥ indicates the phytoremediation and phytoextraction ability of the plant (Ghosh & Singh, 2005). Bioaccumulation Factors were computed using Equation 3.15 (Arnot et al., 2023):

$$\text{BF} = \frac{CP}{CS} \tag{3.15}$$

where cp denotes the elemental concentration in various plant parts and cs represents the concentration of the same metal in the soil from which the plant part was taken. A BF greater than 1 suggests that the plants may act as accumulators; a BF equal to 1 indicates no soil influence, while a BF less than 1 implies that the plant may function as an excluder.

3.6.6 Human Health Assessment

According to Equation 3.16, the non-carcinogenic target hazard quotient (THQ), lifetime carcinogenic risk (LCR) coefficient, carcinogenic risk, and estimated daily dose (EDI) were used to estimate the human health risk resulting from exposure to toxic metals in food crops and water (Wu et al., 2020).

$$THQ = \frac{C \times IR \times EF \times ED \times t}{AT \times BW \times RFD} \tag{3.16}$$

According to Chang et al. (2014), THQ stands for target hazard quotient, Ef for exposure frequency, Ed for exposure duration, IR for food ingestion rate (g/person/d), C for metal concentration in food (mg/kg, on fresh weight basis), RfD for oral reference dose (mg/kg/d), BW for average body weight, and AT for averaging time for non-carcinogens. Exposure frequency (Ef) was 365 days, exposure length (Ed) was 24 years for adults and 6 years for children, and the average time for non-carcinogens (AT) was 8760 and 2190 for children and adults, respectively. Cassava (adult = 421.9 and children = 281.27 g/person/d), cocoyam (adult = 104.1 and children = 69.4 g/person/d), and yam (adult = 137 and children = 91.33 g/person/d) were the root tubers that were consumed at the highest rates (Darko et al., 2022). Adults consumed 2.2 L of water per day, whereas children consumed 1.8 L per day (Ahmad et al., 2021).. Children weighed an average of 15 kg, whereas adults weighed an average of 70 kg (Darko et al., 2017). According to Li et al. (2020), the RfD that was utilized was As = 3x10−4; Cr = 3.0× 10-3; Cu = 4x10−2; Zn = 3.0×10-1; Mn = 1.4x10−1; Ni = 2×10−2; Hg = 3.0×10-4; Pb = 3.60×10-3, and Cd = 5x10−4.

According to (Li et al. 2020), a THQ of more than one suggests a possible danger connected to the pollutant, whereas a THQ of less than one suggests no clear potential harm. The cumulative life cancer risk rating was computed using Equation 3.17 to predict the cancer risk for lifetime exposure (LCR) of Cr, As, Cd, Pb, and H)

$$\mathrm{LCR} = \mathrm{EDI} \times \mathrm{CSF} \qquad (3.17)$$

when the cancer slope factor is CSF. Cr (0.5), As (1.5), Cd (0.38), and Pb (0.0085) were the CSFs utilized (Ahmad et al., 2021). LCR < 10^{-6} denotes no carcinogenic risk, LCR > 10^{-4} denotes a high risk of cancer, and LCR between 10^{-6} and 10^{-4} denotes a risk that is tolerable to humans.

3.7 Statistical analysis and data evaluation

Statistical analyses were performed using JASP and Minitab software (Minitab LLC, Pennsylvania, USA). The data was evaluated using international environmental soil quality guidelines since there are currently no Ghanaian soil quality standards. The Canadian Council of Ministers of the Environment's soil quality guidelines (CCME 2007) and the Dutch Intervention Values (VROM 2000) were selected based on their use in earlier studies conducted in Ghana (Asamoah et al. 2023; Darko et al. 2022). Basic statistical parameters such as range, mean, median, and standard deviation were computed along with correlation analysis, while multivariate statistics in terms of principal component analysis (PCA) were also carried out.

Principal component analysis carried out on the varimax-rotated data using Minitab ver 21 to assess the relationships and variance among the elements (J. Liu et al. 2023). Consideration was given to principal components with eigenvalues greater than 1.0.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Physicochemical properties of soil

Table 4.1: Summary Statistics of Physicochemical Parameters of Soil

Location	pH	EC *(µS/cm)*	SOM *(mg/kg)*	CEC *(meq/100g)*
Mampong (n= 117)				
Minimum	4.79	24.11	0.21	2.73
Maximum	7.81	374.20	2.90	28.48
Mean	6.25	83.82	2.07	9.87
Standard deviation	0.61	54.00	0.62	8.27

Table 4.1 provides a summary of the soil's measured physicochemical characteristics. Soil pH is a critical factor influencing nutrient availability, microbial activity, and metal solubility in soils (Brady & Weil, 2016). The pH values in Mampong range from slightly acidic (4.79) to neutral (7.81), with a mean value of 6.25, which is optimal for most crops. The slight acidity in some areas may be due to organic matter decomposition, leaching of basic cations, or natural soil weathering processes (Awoonor et al., 2024).

The variability in pH (std. dev. = 0.61) suggests that while most soils in Mampong are near neutral, localized variations exist, likely influenced by land use practices and organic matter content (Awoonor et al., 2024). Acidic soils can affect nutrient availability, particularly reducing phosphorus solubility, while near-neutral soils generally favour microbial activity and nutrient uptake (Penn & Camberato, 2019).

Electrical conductivity (EC) is an indicator of soil salinity and ionic strength, influencing plant growth and microbial functions. The low mean EC of 83.82 µS/cm suggests that the soils in Mampong are generally non-saline, which is favourable for agriculture. The variability in EC (std. dev. = 54.00) suggests differences in soil mineral composition and moisture content across different locations.

According to (Abuelgasim & Ammad, 2019), soils with EC values below 400 µS/cm are considered non-saline, meaning Mampong soils do not pose risks of salinity stress to crops. The relatively low conductivity is expected in a non-mining environment, where there is minimal contamination from heavy metals and salts, unlike mining areas, where EC values are often elevated due to metal leaching (Dusengemungu et al., 2022).

Soil organic matter (SOM) represents the organic matter content in soil, which influences soil structure, water-holding capacity, and nutrient availability. The mean SOM of 2.07 mg/kg indicates that the soils have a moderate organic matter content, which is essential for microbial activity and soil fertility (Ababio et al., 2020)

Higher SOM values are associated with better soil structure and increased cation exchange capacity (CEC), which enhances nutrient retention. The relatively low SOM variability (std. dev. = 0.62) suggests a consistent organic matter distribution in the region, likely due to natural vegetation cover and minimal disturbance from industrial activities (B. Liu et al., 2019).

Cation exchange capacity is a measure of the soil’s ability to retain and exchange essential nutrients like calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+}). The wide CEC range (2.73 – 28.48 meq/100g) indicates that some areas have highly fertile soils, while others may have low nutrient retention (Solly et al., 2020).

The mean CEC value of 9.87 meq/100g suggests moderate nutrient-holding capacity, which is beneficial for crop growth and soil fertility. However, the high standard deviation (8.27) highlights significant variation in soil fertility across different sampling sites. This could be attributed to differences in clay content, organic matter levels, and parent material composition (Zhang et al., 2023).

4.2 Activity Concentration of 238U, 232Th, and 40K in Soil

Naturally occurring radioactive materials (NORMs) such as uranium-238, thorium-232, and potassium-40 are present in varying concentrations in the Earth's crust. The activity concentrations of these radionuclides in soil influence radiological exposure levels, which have implications for environmental safety and public health.

In this study, the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in soil samples from Mampong, a non-mining area in Ghana, are examined. The findings are compared with global averages reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000) and previous studies conducted in Ghana to assess potential radiological hazards.

According to Table 4.2, the activity concentration of ^{238}U in Mampong soil was 97.14 Bq/kg on average, with a range of 44.86 Bq/kg to 144.96 Bq/kg. The mean ^{232}Th concentration was 240.18 Bq/kg, with a range of 91.66 Bq/kg to 430.17 Bq/kg. The mean activity concentration of ^{40}K was 191.18 Bq/kg, with a range of 72.84 Bq/kg to 390.46 Bq/kg. As reported by UNSCEAR in 2000, the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in the analyzed soil exceeded the global average values of 30 Bq/kg, 35 Bq/kg, and 400 Bq/kg, respectively. The results indicate that ^{238}U and ^{232}Th activity concentrations are significantly elevated, while ^{40}K levels are relatively lower when compared to global averages.

The data also suggests that Mampong soils are naturally enriched in ^{238}U, ^{232}Th, and ^{40}K, and are significantly depleted compared to global averages. This discrepancy may be attributed to the geological composition of the area, with the presence of uranium- and thorium-bearing minerals such as zircon and monazite. Additionally, potassium depletion could be due to leaching and soil formation processes that favour the loss of potassium over time. The existence of rocks with a high concentration of these radionuclides in the area may be the cause of the higher activity concentration of radionuclides than the global average, which might raise NORM levels.

A study from related national and international studies shows that while (Joel et al., 2019) and (Ademola et al., 2014) reported similar results in Nigeria, (Darko et al., 2015) and (Moipone et al., 2021) reported lower activity concentrations of radionuclides in Ghana. (Aliyu et al., 2015) reported a higher ^{238}U activity concentration of 185.48 Bq/kg in Nigeria, but (Ehsan et al., 2020) reported lower quantities in Bangladesh. In comparison, Mampong soils exhibit significantly higher ^{238}U and ^{232}Th activity levels but much lower ^{40}K concentrations. These variations highlight the influence of geological diversity on natural radioactivity levels across different regions in Ghana. Such findings further suggest that soil composition, mineralization, and environmental conditions play significant roles in radionuclide distribution.

In addition to their radium equivalent activity, external and internal hazard indices, annual effective dose equivalent (AEDE), and excess lifetime cancer risk (ELCR), in soil samples from multiple locations were assessed. The average computed radium equivalent for Mampong was 455.31 ± 164.89 Bq/kg, with a range of 181.54 to 740.38 Bq/kg. The mean radium equivalent activity exceeded 370 Bq/kg, which is the acceptable threshold set by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000).

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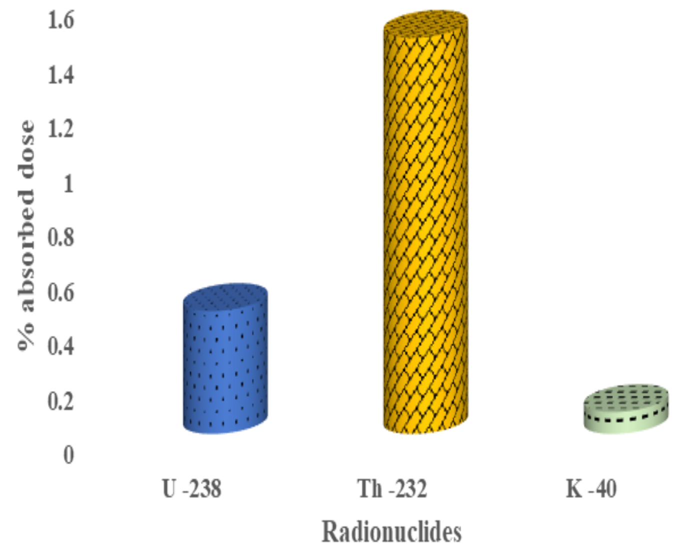

Figure 4.1: Percentage Absorbed Dose Rate of Radionuclides in Soil

In this study, the average external (Hex) hazard index was more than 1, indicating that the population is exposed to gamma radiation from the outside. Residents of Mampong encounter an average gamma absorbed dose rate of 197.92 ± 71.22 nGy/h in outdoor air due to ^{238}U, ^{232}Th, and ^{40}K in soils as shown in Table 4.1. For uncontaminated areas, the average values are higher than the worldwide mean outdoor absorbed dose rate in the air (60 nGy/h) (UNSCEAR, 2000). The proportionate contributions of ^{238}U, ^{232}Th, and ^{40}K to the total absorbed gamma radiation rates determined for the soil samples are shown in Figure 4.1. Although potassium isotopes are abundant in the soil, their contribution to the absorbed dose rate is negligible. The low conversion factor of the ^{40}K radioisotopes might be the cause of this. The average annual effective dosage that Mampong residents got was 0.24 ± 0.06 mSv/y, which is below the 0.3 mSv/y recommended safe limit (UNSCEAR, 2000). All of the study's anticipated elevated lifetime cancer risk estimates fell below the predetermined cut-off of 0.0029 Sv^{-1} (UNSCEAR, 2000). This suggests that there is no chance of developing cancer in the lifespan of those exposed to this radiation.

Table 4.2: Radium equivalent, gamma dose rate, and annual effective dose rate of ^{238}U, ^{232}Th and ^{40}K in soil

Location				**Raeq**	**AEDR**	**Hex**	**Hin**	**ELCR**
ID	**^{238}U**	**^{232}Th**	**^{40}K**	**[Bq.kg^{-1}]**	**[msv.y^{-1}]**	**[msv.y^{-1}]**		**[Sv^{-1}]**
MCaS1	144.96	296.58	256.98	588.86	0.31	1.59	1.98	0.00110
MCAS19	101.68	430.17	306.02	740.38	0.39	2.00	2.27	0.00137
MCaS38	82.61	188.43	138.95	362.77	0.19	0.98	1.20	0.00068
MCaS9	44.86	91.66	72.84	181.54	0.10	0.49	0.61	0.00034
MCOS2	96.35	225.25	151.07	430.09	0.23	1.16	1.42	0.00080
MCoS3	93.00	170.00	199.00	351.42	0.19	0.95	1.20	0.00066
MCoS4	74.17	178.49	107.78	337.71	0.18	0.91	1.11	0.00063
MYaS1	101.08	212.22	125.02	414.18	0.22	1.12	1.39	0.00077
MYaS2	118.45	266.62	255.01	519.35	0.28	1.40	1.72	0.00097
MYaS3	99.57	200.21	99.80	393.55	0.21	1.06	1.33	0.00073
MYaS7	111.79	382.31	390.46	688.56	0.37	1.86	2.16	0.00128
Mean	97.14	240.18	191.18	455.31	0.24	1.23	1.49	0.00085
SD	25.47	98.10	99.69	164.89	0.09	0.45	0.50	0.00031
Minimum	44.86	91.66	72.84	181.54	0.10	0.49	0.61	0.00034
Maximum	144.96	430.17	390.46	740.38	0.39	2.00	2.27	0.00137

4.3 Activity Concentrations of ^{238}U, ^{232}Th, and ^{40}K in Food Crops

Table 4.2 presents the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K that were found in root tubers that were acquired from different farms in Mampong.

The presence of naturally occurring radioactive materials (NORMs) in the environment is a significant concern due to their potential health risks when they accumulate in food chains. Radionuclides such as uranium-238, thorium-232, and potassium-40 exist in varying concentrations in soils and can be absorbed by crops, leading to internal exposure upon human consumption. Understanding the activity concentration of these radionuclides in staple food crops is essential for assessing potential radiological health hazards. This study investigates the levels of ^{238}U, ^{232}Th, and ^{40}K in cassava, cocoyam, and yam grown in Mampong and evaluates their soil-to-plant transfer factors (TFs).

Table 4.3: Activity concentration (Bq/kg) in root tubers and Soil-to-plant crop transfer factor of the radionuclides

Location	**Food Type**	**Activity concentration (Bq/kg)**		**Soil-to-plant crop transfer factor**		
		^{238}U	**^{232}Th**	**^{238}U**	**^{232}Th**	**^{40}K**
Mampong	*Cassava*	93.53 ± 41.63	251.71 ± 145.47	0.17(2.46)^{a}	0.07(2.24)^{a}	8.69 (1.86)^{a}
	Cocoyam	87.84 ± 11.96	191.25 ± 29.75	0.30(1.62)^{a}	0.12(1.41)^{a}	14.13(1.51)^{a}
	Yam	107.72 ± 8.99	265.34 ± 83.16	0.25(2.57)^{a}	0.15(3.39)^{a}	6.69 (3.72)^{a}

The activity concentration of ^{238}U, ^{232}Th, and ^{40}K in cassava, cocoyam, and yam from Mampong varies significantly. The highest concentration of ^{238}U was observed in yam (107.72 ± 8.99 Bq/kg), followed by cassava (93.53 ± 41.63 Bq/kg) and cocoyam (87.84 ± 11.96 Bq/kg). Similarly, ^{232}Th activity concentration was highest in yam (265.34 ± 83.16 Bq/kg), followed by cassava (251.71 ± 145.47 Bq/kg) and cocoyam (191.25 ±

29.75 Bq/kg). Conversely, ^{40}K activity was highest in cocoyam (14.13 Bq/kg) and lowest in yam (6.69 Bq/kg).

These findings suggest that different crops exhibit varying capacities for radionuclide uptake, likely due to differences in root structure, soil chemistry, and nutrient absorption mechanisms (Chen et al., 2021). The high concentrations of ^{238}U and ^{232}Th in yam suggest that it has a greater tendency to accumulate these radionuclides from the soil. On the other hand, the relatively higher activity of ^{40}K in cocoyam implies that this crop is more efficient in potassium uptake, which (Mbah & Njoku, 2023) and growth (Mbah & Njoku, 2023). The TF values for ^{238}U, ^{232}Th, and ^{40}K in cassava, cocoyam, and yam exhibit significant variations. The highest ^{238}U TF (0.30) was observed in cocoyam, indicating that cocoyam has a higher affinity for uranium absorption. Yam exhibited the highest ^{232}Th TF (0.15), while cocoyam had the highest ^{40}K TF (14.13), further supporting its efficient potassium uptake.

The International Atomic Energy Agency (IAEA) TF values range from 2.6×10^{-4} to 1.9×10^{-1}, with a Geometric Mean (GM) of 0.019 (IAEA, 2011a). There were no significant differences ($p>0.05$) in the geometric mean of the TFs for ^{238}U between the various root tubers. However, it is pertinent to highlight that the TF values for ^{238}U in cassava, cocoyam, and yam in the current study markedly exceed the geometric mean value of 0.005 reported by the IAEA for ^{238}U. However, the results of the TF of ^{238}U from previous research in Ghana and several neighbouring countries (Nigeria and Cameroon) are comparable to the majority of the values found for the present study, as shown in Table 4.4.

Table 4.4: Mean of soil to plant crop transfer factor values obtained in the present study and results reported from other countries

Food Category	Country	Soil to plant TFs		References
		^{238}U	^{232}Th	
Cassava	Ghana	0.11	0.12	(Darko et al., 2015)
Yam		0.12	0.11	
Cassava	Ghana	0.11	0.05	(Doyi et al., 2018)
Cassava	Nigeria	1.82	0.72	(Ekpene et al., 2021)
Cassava	Cameroon	1.22	0.41	(Ben-Bolie et al., 2013)
Cocoyam		0.55	0.21	
Cassava	Nigeria	0.43	0.53	(Bello et al., 2024)
Cassava	Ghana	0.25	0.19	Present study
Cocoyam		0.23	0.11	Present study
Yam		0.21	0.13	Present study
Tubers	Temperate	5.0×10^{-3}	2.0×10^{-3}	(IAEA, 2010)

The TFs of ^{232}Th also did not vary significantly ($p>0.05$) among the locations. Additionally, no significant variation was observed between TFs of ^{232}Th of cassava and cocoyam ($p=0.36$), between cassava and yam ($p=0.56$) and between cocoyam and yam ($p=0.10$). The observed TF values exceed the reported geometric mean (0.002) of soil-to-plant TFs for ^{232}Th by the International Atomic Energy Agency (IAEA, 2011b). However, the results of the TF of ^{238}U from earlier studies from Ghana and neighbouring countries are comparable to the TFs of the current study.

The transfer of naturally occurring radionuclides from soil to plants is significantly influenced by various soil physicochemical properties, including pH, cation exchange capacity (CEC), and soil organic matter (SOM) (Clercq & Gryze, 2016). It indicates that the soil-to-plant transfer of ^{238}U and 232Th is positively correlated (Table 5) with soil pH. This is because, at higher pH values, radioactive materials' solubility might rise due to the formation of more soluble complexes. For instance, in alkaline conditions, uranium forms more soluble species (such as uranyl complexes), enhancing its transfer in soil. Conversely, lower pH often leads to higher ion exchange and adsorption of cations onto soil particles, potentially reducing the mobility of radioactive elements (Caporale & Violante, 2016). The data also show a clear inverse relationship between the amount of organic matter present and the TFs of ^{238}U and ^{232}Th radionuclides from soil to crops. Additionally, the soil cation exchange capacity (CEC) showed an inverse correlation with the TFs of both ^{238}U and ^{232}Th.

Table 4.5: Pearson's correlations of transfer factors of ^{238}U, ^{232}Th, and ^{40}K and physicochemical parameters of soil

	U	Th	K	Ph	EC	CEC
Th	0.97*					
K	-0.69	-0.60				
pH	0.73*	0.58*	-0.48			
EC	0.99*	0.99*	-0.71	0.64		
CEC	-0.07	-0.31	-0.34	0.46	-0.17	
SOM	-0.17	-0.40	-0.14	0.46	-0.28	0.97*

*Correlation is significant at the 0.05 level (2-tailled)

The outcomes suggested that higher soil CEC correlated with reduced transfer of ^{238}U, ^{232}Th, and ^{40}K into the root tubers.

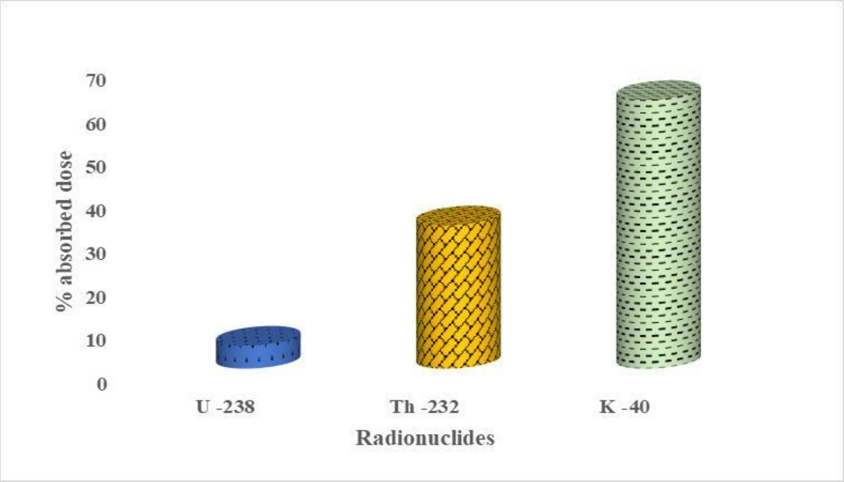

Figure 4.2: Percentage Dose Rate of Radionuclides in Food Crops

Because of its great biological necessity, the element ^{40}K is considered essential for plant growth. As a result, when extra soluble potassium is readily available, plants frequently absorb it. Inside human cells, the ^{40}K content is typically regulated and is rarely a cause for alarm. The use of NPK fertilizer to increase crop yields in the study area may be connected to elevated levels of ^{40}K in farming districts. The content of ^{232}Th in root tubers was consistently higher than that of ^{238}U, as depicted in Figure 4.2.

It is necessary to consider factors other than the reported activity concentration when evaluating the effects of natural radioactivity. The impact is assessed using health impact indicators such as Adult Lifetime Fatality Cancer Risk, Adult Estimated Lifetime Hereditary Effects and Committed Effective Dose (ET) from the consumption of contaminated food crops. The estimated committed effective dose values due to the consumption of cassava, cocoyam and yam for the various age groups (as shown in Figure 4.3), significantly exceed the World Health Organization's recommended safe limit of 0.1 mSv/y (World Health Organization, 2013), indicating that the consumption of these primary food products poses a significant radiological health risk. The average annual effective radiation is 3.93 millisieverts per year.

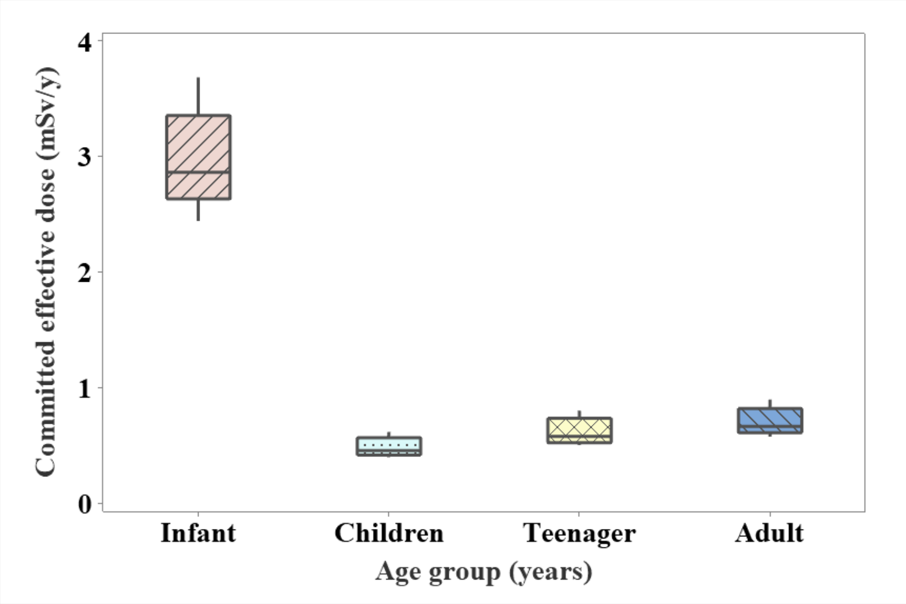

Figure 4.3 Committed Effective Dose due to Consumption of Food Crops for the various age groups

One cancer death per 10,000 to one million people is considered tiny or insignificant, according to the United States Environmental Protection Agency's (USEPA) definition of the acceptable cancer fatality risk, which falls between 1.0 x 10^{-6} and 1.0 x 10^{-4}. According to analysis portrayed in Table 4.6, people in the investigated group who ate cassava, cocoyam, and yam had estimated LFCR and ELHE that were higher than the USEPA-established acceptable risk levels (USEPA, 2019).

Table 4.6: Activity Concentration, Annual Effective dose and Estimated Cancer

risks and Hereditary Effects on Adult member of the Public due to consumption of Cassava, Cocoyam and Yam

		^{138}U $\times10^{1}$	^{232}Th $\times10^{1}$	^{40}K $\times10^{3}$	Total Effective Dose E_T Adult(mSv/y)	FCR $\times10^{-4}$	LFCR $\times10^{-2}$	SHE $\times10^{-6}$	LSHE $\times10^{-4}$
Mampong	***Mean***	2.70	4.92	1.67	3.93	2.16	1.51	7.86	5.50
	Std. Dev.	2.95	9.8	0.58	3.66	2.01	1.41	7.32	5.12
	Minimum	1.08	1.21	0.39	1.70	9.37	6.56	3.41	2.39
	Maximum	11.20	34.60	2.38	14.80	8.14	5.69	29.60	20.70

ET = Total Annual Effective, FCR = fatality cancer risk to adult per year, LFCR = lifetime fatality cancer risk to adult, SHE = severe hereditary effect in adult per year, ELHE = Estimated lifetime hereditary effect in adult.

Figure 4.4 shows the geographical distribution of the three naturally occurring radionuclides that were measured within the Mampong village. It shows that the distribution of ^{238}U, ^{232}Th, and ^{40}K in the research locations is not uniform. The geological and lithological variability of the various regions, as well as land use, including agricultural and residential areas, are the causes of the variance in the distribution of ^{238}U, ^{232}Th, and ^{40}K that has been documented. A consistent pattern can be seen on the map showing the geographical distribution of ^{238}U, ^{232}Th, and ^{40}K in Mampong soil. The radioactive concentrations in the southern and western zones are high to very high.

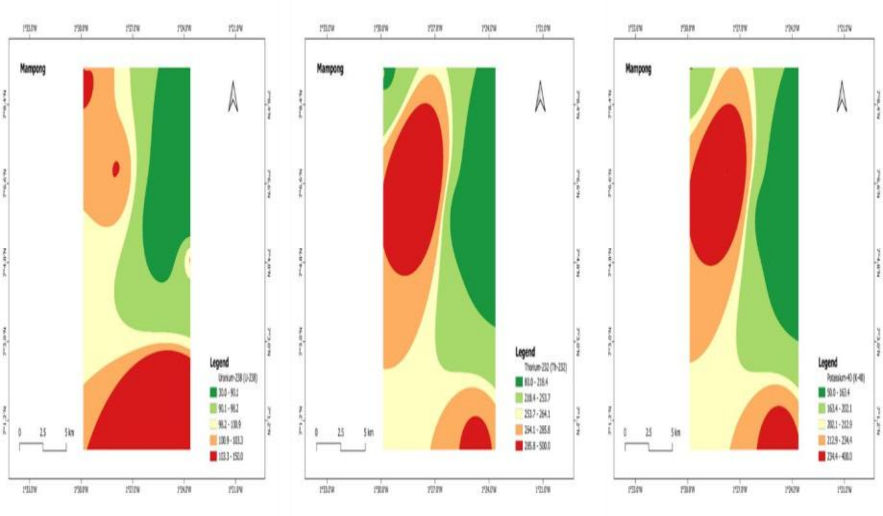

Figure 4.4 shows a spatial distribution of the radionuclides (^{238}U,$^{234\text{Th}}$ and ^{40}K

4.4 Potentially Toxic Elements in Soils

4.4.1 Arsenic

The mean value of arsenic in Mampong soils was 6.61 ± 4.97 mg/kg, with a range of 2.45 mg/kg to 5.16 mg/kg. The average concentration of arsenic was lower than the Dutch Intervention value of 55.00 mg/kg (VROM, 2000) and the CCME soil quality recommendation of 12 mg/kg (CCME, 2007). An earlier study conducted in the country found levels below the arsenic limits. (Darko et al., 2020) found that agricultural soils from Akumadan and Offinso had arsenic concentrations of 3.8 mg/kg and 5.1 mg/kg, respectively. Fossil fuel combustion in cars, anthropogenic activities that contribute to elevated arsenic levels in the research area include the use of paint, herbicides, pesticides, fungicides, and food preservatives (Rahaman et al., 2021), arsenic is a non-essential element that can have a number of harmful impacts on human health, such as neurological disorders, lung disorders, cardiovascular diseases, hypertension, and peripheral and cutaneous lesions.

4.5 Lead

The mean concentration of lead in Mampong soils is 6.2 ± 13.18 mg/kg, with values ranging from 3.00 mg/kg to 142.9 mg/kg. This is far lower than the Dutch Intervention Value of 210 mg/kg (VROM, 2000) and the CCME soil quality guidelines of 70 mg/kg (CCME, 2007).The results were similar to the value (6.09 ± 6.35), obtained in Kenya (Rahaman et al., 2021), but lower than those reported in agricultural soils in earlier studies from Ghana (Roseline et al., 2016). According to Liu et al., (2020), lead is a highly bioavailable hazardous element that has a short mobility and retention period in topsoil. Pb bioaccumulation in soil might endanger long-term human exposure and harm human health, leading to anaemia, weight loss, pregnancy complications, renal dysfunction, and in extreme cases, cancer (Collin et al., 2022).

4.6 Cadmium

One of the most important pollutants in soil, cadmium, showed amounts ranging from 5.58 mg/kg to 679.8 mg/kg, with a mean of 87.96 ± 115.1 mg/kg. This is much higher than the regulatory limit established by the Dutch intervention (12 mg/kg) ((VROM, 2000) and CCME (10 mg/kg) ((CCME, 2007). These amounts were greater than those found in agricultural soils in earlier research from Nigeria that is 5.7 ± 4.0 mg/kg as reported by (Egwu & Agbenin, 2013) and in Ghana 0.05 mg/kg as reported by (Bortey-Sam et al., 2018). The application of synthetic phosphate fertilizer to the soil through farming operations is the cause of the increased Cd concentrations in the study region. Chlorosis and stunted development are linked to high levels of Cd in soils, which prevent plants from growing and eventually cause them to necrotize (Haider et al., 2021).

4.7 Zinc

The zinc concentrations in Mampong soils exhibit a broad range, from 5.59 mg/kg to 748.31 mg/kg, with a mean value of 37.53 ± 74.15 mg/kg. This is significantly lower, five times below the CCME-mandated acceptable limit of 200 mg/kg and 19 times lower than the Dutch Intervention value of 720 mg/kg(VROM, 2000). Compared to previous studies, these levels are also lower than those reported in Ghanaian agricultural soils, including 50.2 mg/kg (Darko et al., 2022) and 52.45 mg/kg (Asamoah et al., 2021) , as well as Nigerian agricultural soils, which recorded 502.8 mg/kg (Hamid et al., 2019). Zinc is an essential trace element for both plants and animals, and its low availability in agricultural soils can adversely affect crop productivity and nutritional quality (Feng et al., 2021).

4.8 Copper

Mampong soils had Cu levels ranging from 8.92 mg/kg to 114.2 mg/kg, with an average of 13.88 ± 9.78 mg/kg. This is much less than the Dutch intervention value of 190 mg/kg and the CCME soil quality guideline of 63 mg/kg (CCME, 2007) (VROM, 2000). Researchers have previously reported different concentrations. For instance, zinc values of 16.5 mg/kg were observed at Offinso by (Darko et al., 2022). Whereas (Asamoah et al., 2021) also reported a value of 24.52 mg/kg in Sunyani. Copper is persistent in soil due to its poor water solubility, which impacts plant growth, root system development, and seed germination (Fagnano et al., 2020)

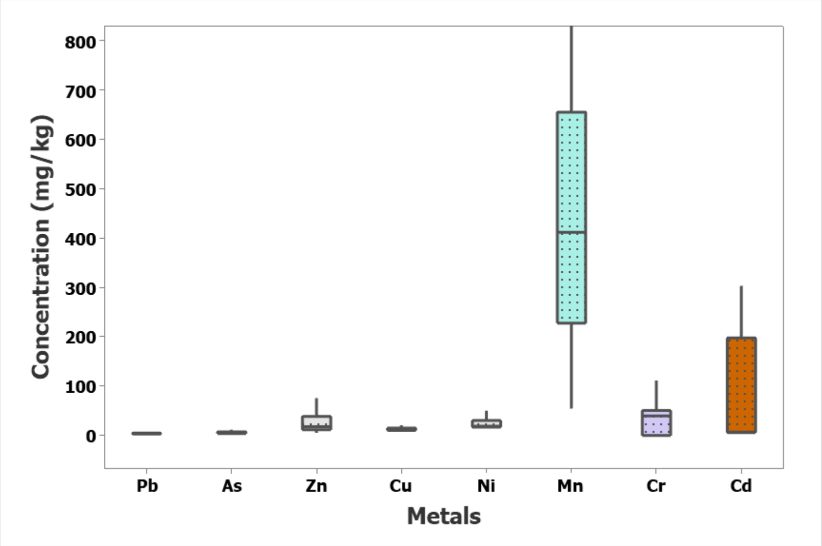

Figure 4.5: Concentration of Potentially Toxic Elements (mg/kg) in Mampong Soil

4.9 Nickel

Nickel concentrations in Mampong soils ranged from 15.80 mg/kg to 257 mg/kg, with an average of 36.26 ±38.61 mg/kg recorded. The measured mean nickel content was below the Dutch intervention value of 210 mg/kg (VROM, 2000) and the permissible level established by CCME soil quality recommendations of 45 mg/kg CCME, 2007). Although the current study's values were lower than the 47.12 mg/kg found in Nigeria (Kayode et al., 2022), they were greater than those found in Ghana's agricultural soils: Akomadan, where they were 20.2 mg/kg (Darko et al., 2022) and 0.343 mg/kg in Abuakwa South (Baah et al., 2021). The application of phosphatic fertilizers to the soil is the cause of the increased Ni content values found in the current study According to Hassan et al. (2019), Ni is necessary for plant growth at low concentrations but inhibits root growth and produces chlorosis in plants at high concentrations.

4.10 Chromium

The mean value of Cr in Mampong soils was 31.92 ± 27.51 mg/kg, which is almost half of the 64 mg/kg recommended by CCME soil quality standards (2007) and twelve times lower than the Dutch intervention value of 380 mg/kg (VROM, 2000). The values of Cr in Mampong soils varied from 0.25 mg/kg to 111.7 mg/kg. Human endeavours like farming might be blamed for this. Different values have been reported in previous investigations. For instance, (Darko et al., 2022), and (Bortey-Sam et al., 2015) reported greater values of 82.8±11.4 mg/kg (Amansie) and 16 ± 10 mg/kg (Tarkwa), respectively, than the current study, whereas Baah et al., 2021 reported lower values of 0.42 mg/kg (Abuakwa). Hair loss, allergic dermatitis, and nasal lining irritation have all been linked to elevated Cr levels (Cork et al., 2009).

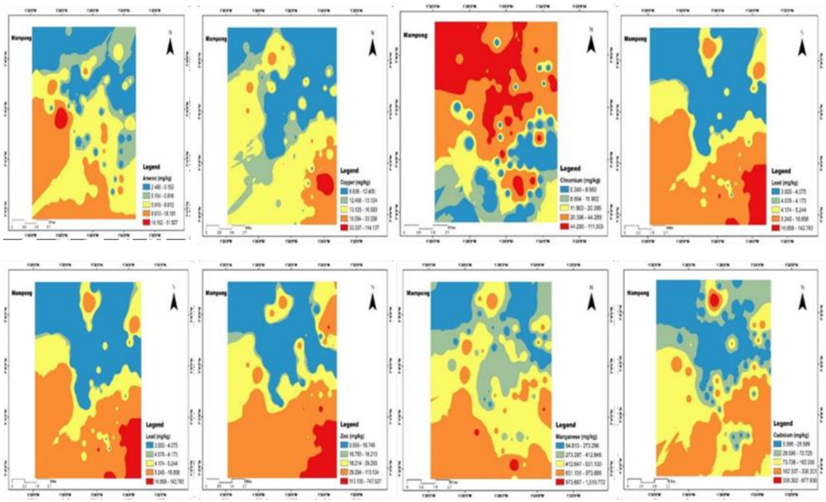

Figure 4.6 Spatial Distribution of Potentially Toxic Elements in Soils

The regional distribution of metals in Mampong's surface soils is shown in Figure 4.6, with the north, east, and central regions showing the lowest concentrations of arsenic.

Nonetheless, the western and southern regions have high to extremely high concentrations.

Mercury and copper concentrations were extremely low at the site, with the north having the lowest values. On the other hand, the northern part had elevated levels of chromium, which can be attributed to human activities such as fertilizer applications and agricultural production. The southwest region of Mampong, which is home to the auto mechanic activities, has a concentration of lead and zinc. The primary cause of the elevated lead level may be a result of accumulation from batteries. Cadmium, manganese, and nickel all had comparable patterns of geographical distribution. While they are modest in the west, they are high in the south and quite high in the northern regions.

4.11 Potentially Toxic Elements in Root Tubers

The average concentration (mg/kg) of metals and root tubers often followed this pattern: Mn (30.97) > Cr (12.13) > Ni (9.85) > Zn (8.02) > Cu (5.92) > Cd (4.81) > Pb (1.68) > As (1.24). The range of Cr concentrations was 0.45 mg/kg to 47 mg/kg. Compared to other metals examined, the amounts of Mn in the food crops were quite high. In cocoyam and cassava, the Mn content varied from 16.68 mg/kg to 1058.7 mg/kg. This fluctuation illustrates the research area's comparatively greater range in Mn concentration. The content of copper in cocoyam ranged from 4.59 mg/kg to 20.25 mg/kg in cassava. Pb concentrations in the sample sites ranged from 1.50 mg/kg in cassava to 5.33 mg/kg in cocoyam, with a very consistent distribution. The levels of Cd in cocoyam and cassava ranged from 1.99 mg/kg to 181.08 mg/kg, respectively. As varied within the range of 1.24 ± 0.74 mg/kg, from 1.08 mg/kg in cassava to 7.65 mg/kg in cocoyam. Zn levels in cocoyam ranged from 2.75 mg/kg to 31.04 mg/kg in cassava. The average Cr content in the root tubers was 5.25 ± 12.13 mg/kg. The concentration of Cr is found in the root tubers above the WHO-accepted threshold of 1.0 mg/kg. Because Cr is essential for glucose metabolism, a lack of it impairs human development and creates problems (Monga et al., 2022). For both plants and animals, Mn is an essential element. Mammals with Mn deficiencies have significant skeletal and reproductive abnormalities (Studer et al., 2022). With a mean value of 30.97 ± 117.88 mg/kg, Mn fell inside the 500 mg/kg WHO-recommended safe limit. Cu is essential for the synthesis of haemoglobin and is a component of several enzymes. The estimated average value of Cu was 5.92 ± 2.00 mg/kg, which was less than the WHO-recommended threshold of 30 mg/kg. Zn is a vital trace metal that both people and animals need. Zn deficiency causes taste loss and stunted development in both humans and animals, whereas increased Cu concentrations above 40 mg/kg have a toxic impact that includes nausea, irritability, loss of appetite, and muscle stiffness and discomfort. The root tubers had an average zinc content of 8.02 ± 6.21 mg/kg, which was less than the 73.3 mg/kg suggested safe limit set by WHO (WHO, 2013). Food consumption is the source of cadmium in the human body. The root tubers' average Cd content was found to be higher than the cutoff point of 0.2 mg/kg. People who consume more yam, cocoyam, and cassava than the recommended daily allowance of cadmium may have renal failure (Abdullahi, 2023). With a maximum limit of 10 mg/kg, Pb had a mean of 1.08 ± 0.43 mg/kg. The calculated Pb content was within the advised range. Human lung damage and renal failure are caused by the hazardous heavy metal lead (Bortey-Sam et al., 2018). Humans obtain their Ni requirements via consuming and digesting food. Lung and nasal cavity malignancies are caused by exposure to high Ni concentrations (Nabuuma, 2021). The average Ni content in the root tubers was 9.85 ± 2.76 mg/kg. This number is less than the 70 mg/kg threshold level (CCME, 2007).

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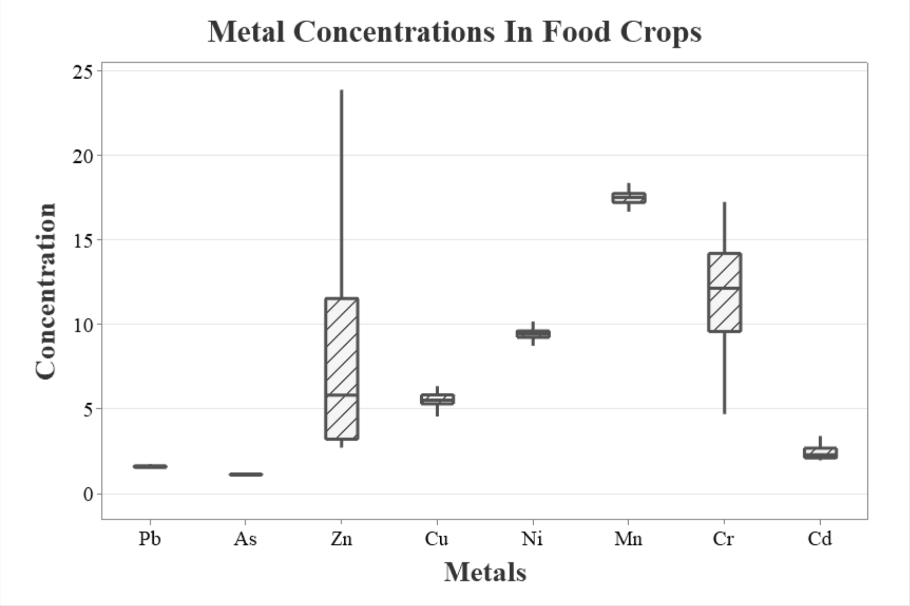

Figure 4.7: Metal Concentrations in Food Crops

4.12 Correlation Analyses

As seen in Figure 4.8, correlation analysis was used to examine the connection between the metal concentrations in the soil samples and the physicochemical parameters (CEC, pH, EC, and TOC). With the exception of As and Cr, which had a mild association that was statistically insignificant ($p > 0.05$), there was a strong positive significant correlation between CEC and pH, EC, TOC, and all the metal concentrations. Except for Cr, which displayed a highly significant positive connection, there was a modest link between EC and the metal concentrations. There was a somewhat favourable relationship found between pH and Pb, Zn, and Cd.

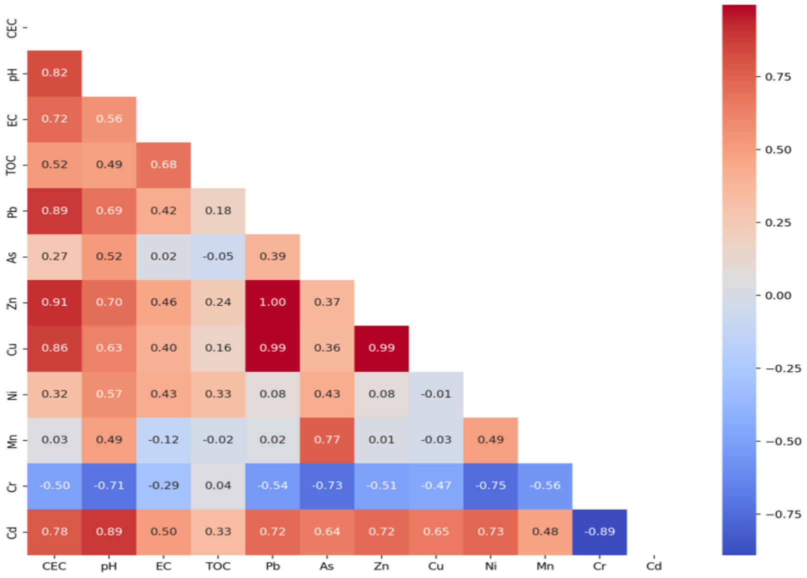

Figure 4.8: Correlation Analysis Between the Metals and the Physicochemical Parameters

The moderately positive association that has been discovered suggests that the concentration of the metal rises with an increase in pH. However, as the soil's pH rose, the concentration dropped. It is important to remember that this connection does not prove that the pH and the measured metal concentrations are causally related. Both pH levels and the presence of these metals may be influenced by confounding variables such as geographic location, environmental circumstances, and other factors. Pb exhibited a modest negative association with As (-0.044) and Cr (-0.145) and a very strong connection with Zn (0.975), Cu (0.900), and Cd (0.686). In soil samples, the strong correlation coefficient between metals indicates interdependence and a shared source.

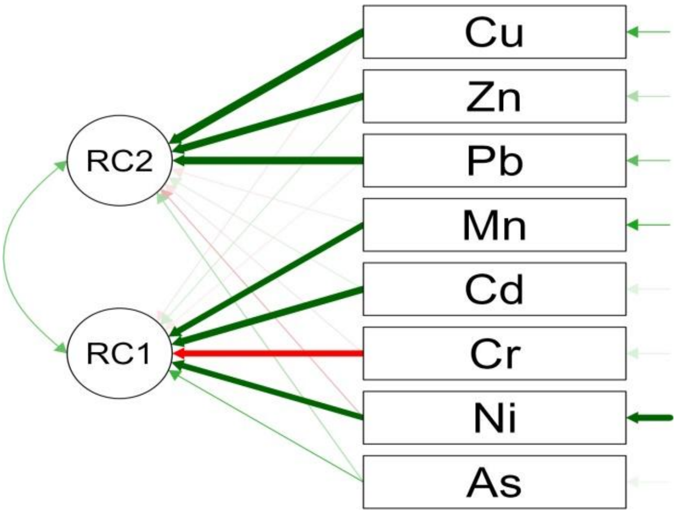

Figure 4.9: Principal Component Analysis

Figure 4.9 explains the variation and commonality as well as the factor loading component's outcomes. The overall variation was 74.1% due to the two-factor component that was found. Component 1 has a substantial load on Cd, Cr, Mn, and Ni and accounts for 46.0 of the total variations. pointing to a typical source of trash contamination. Given that prolonged usage of phosphate fertilizers is the source of Cd accumulation in agricultural soils. Farming operations may also have an impact on other metals in PC 1 that have a strong correlation with Cd. 28.1 percent of the overall variations were explained by the second component, which is loaded with Pb, Cu, and Zn. Component 2's metals might have a geogenic origin.

Bioconcentration Factor

The soil-to-plant transfer of potentially toxic elements is influenced by the properties of the soil, the chemistry of the metals, and the type of plant involved. The average bioconcentration factor of elements in the various food crops is shown in Table 4.7.

When the bioconcentration factor (BCF) surpasses one, this indicates that the plant has accumulated chemical components. A bioconcentration factor near 1 suggests that the elements have little influence on the plants, but a BCF value less than 1 indicates that the elements have not been absorbed (Amoakwah et al., 2020). According to the soil–to-plant uptake factors, the accumulation of elements in crops that were examined was generally low, except for cassava, which recorded a significant enrichment of chromium.

Table 4.7: Bio-accumulation factor of heavy metals for Cassava, Cocoyam and Yam

	Pb	As	Zn	Cu	Ni	Mn	Cr	Cd
Cassava	0.42	0.23	0.52	0.47	0.46	0.08	3.65	0.30
Cocoyam	0.45	0.21	0.63	0.53	0.53	0.09	0.25	0.39
Yam	0.50	0.31	0.43	0.53	0.60	0.10	0.97	0.45

Toxic metal contamination

This study utilised the contamination factor (CF), geoaccumulation index (Igeo), along with potential ecological risk index to assess if the sources of elemental contamination were anthropogenic (Waqeed Mahdi Hadif et al., 2020).

Geoaccumulation index (Igeo)

The computed Igeo values are displayed in Table 4.8. The Igeo values for As, Cr, Cu, Mn, Ni, Pb, and Zn indicated no contamination in the study area. The findings indicated significant levels of cadmium contamination in the surface soil in the study area. (Asamoah et al., 2021) reported elevated concentrations of cadmium are present in the surface soils of Ghana.

Table 4.8: Mean pollution index of soil in the study area.

	Pb	As	Zn	Cu	Ni	Cr	Cd	Mn	Ti	V
Igeo	-2.69	-1.74	-2.65	-2.38	-1.91	-3.96	5.77	-1.8	-3.04	-3.63
CF	0.31	0.51	0.39	0.3	0.53	0.35	293.2	0.54	0.74	0.4

Igeo = Geoaccumlation Index; CF = contamination Factor

Contamination Factor (CF)

The levels of contamination for different elements in soils obtained from the study area are displayed in Table 4.8. The findings indicated that the elements, Pb, Cu, Ni, Cr and Mn recorded low contamination levels, while Cd recorded a very high contamination in the study area.

Ecological risk

To evaluate elemental contamination in the soil regarding ecological danger, prospective ecological risk indices were calculated, with the findings displayed in Table 4.9. Potential ecological risk signifies the local environment's response and the degree of metal toxicity.

Table 4.9: Potential Ecological Risk Index (PERI) for soil samples

Metal	Amansie	Konongo	Mampong
	PERI	**PERI**	**PERI**
As	23.19	31.77	5.08
Cd	721.52	732.02	8796.11
Cu	2.14	2.67	1.54
Cr	1.79	1.93	0.71
Mn	0.36	0.53	0.54
Ni	1.47	1.46	2.66
Pb	1.00	1.33	1.55
Zn	0.42	0.53	0.39

The metals exhibited diverse risk levels in the study areas. The sequence was Zn < Mn <

Cr < Pb < Ni < As < Cd. The ecological risk linked to the metals was generally low, except for Cadmium, which showed a notably elevated risk in the study area.

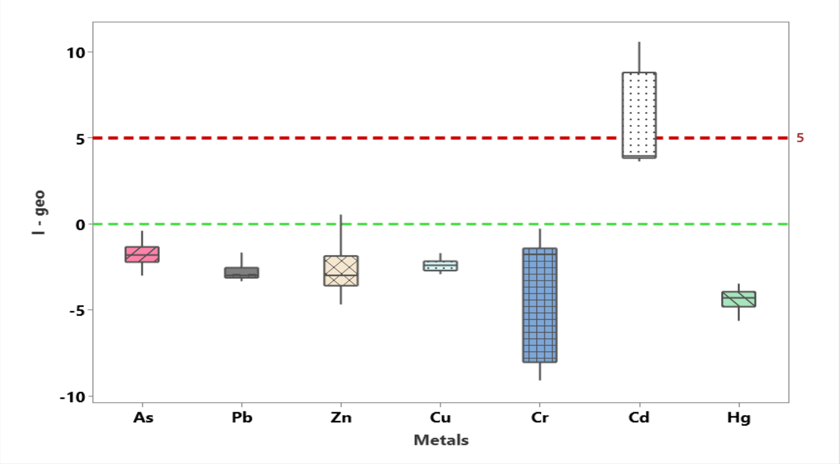

Figure 4.10: Geo- accumulation Index (Igeo)

4.13 Health Risk Assessment

In order to determine the non-carcinogenic health risk associated with consuming yam, cocoyam, and cassava, the target hazard quotient was calculated. The THQ indicates the degree of worry but does not quantify the health risk that residents face from consuming agricultural crops that expose them to trace metals (Baah et al., 2021). A THQ < 1 generally indicates that the contaminants being studied pose no probable health risks due to the present degree of exposure to a certain drug. The THQ of the metals under study through the eating of root tubers is shown in Table 4.4. However, when THQ > 1, it suggests that there may be a health risk. The sequence in which the THQ dropped for both adults and children was Cr > Zn > Mn > Cd > Ni > As > Pb > Cu. With the exception of the Zn, Cr, Cd, and Mn THQ values in cocoyam, which were more than 1, the majority of the THQ values determined from the root tubers in the tested community were below 1 for both adults and children. This implies that eating these root tubers may not negatively impact residents of Mampong.

Table 4.10: **Hazard Quotient (HQ) in mg/kg/day and Hazard Index (HI) of Cassava, Cocoyam and Yam for Adults and Children in Mampong**

Food Items		**Pb**	**As**	**Zn**	**Cu**	**Ni**	**Cr**	**Mn**	**Cd**
Cassava	*Child*	0.05	0.27	3.49	0.00047	0.63	118.18	3.25	0.68
	Adult	0.03	0.17	2.24	0.00030	0.17	75.97	2.09	0.17
Cocoyam	*Child*	0.01	0.08	1.26	0.00029	0.17	28.85	5.95	1.41
	Adult	0.01	0.05	0.81	0.00019	0.05	18.54	3.83	0.05
Yam	*Child*	0.02	0.09	0.84	0.00158	0.22	30.97	3.21	0.77
	Adult	0.01	0.06	0.54	0.00102	0.06	19.91	2.06	0.06

The hazard index (HI), which is the total of the THQ values for metals from eating tubers in Mampong, is also suggested in Table 4.10. The study community's total HI for both adults and children was more than 1. The THQ levels of Cr, Zn, and Mn are the cause of this high value. The high HI found in Mampong suggests that the local population may be at risk for heavy metal-related illnesses. Table 4.11 lists the carcinogenic risk values for As, Cr, Cd, Ni, and Pb in adults and children who eat root tubers. The Mampong community's carcinogenic risks for adults who consumed cassava, cocoyam, and yam varied from 2.28 × 10^{-5} to 3.80 × 10^{-2}, while the carcinogenic risks for children who consumed these foods ranged from 3.54 × 10^{-5} to 7.44 × 10^{-2}. The risks of cancer Because Cd, Cr, and Ni show that there is a high risk of cancer from trace elements, Mampong's cassava, cocoyam, and yam may not be safe for human consumption due to the likelihood of developing cancer in the lifetime from exposure to toxic metals over time. Carcinogenic risk values also make it clear that youngsters are more likely to be at risk for health problems as a result of eating these root tubers (Table 4.11).

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Table 4.11: Human Health Risk Assessment for Carcinogenic Metals

Food Items		**Pb**	**As**	**Ni**	**Cr**	**Cd**
Cassava	*Child*	1.29E-04	6.44E-03	7.44E-02	5.91E-02	8.44E-03
	Adult	8.27E-05	4.14E-03	5.80E-03	3.80E-02	2.62E-03
Cocoyam	*Child*	3.54E-05	2.03E-03	2.05E-02	1.44E-02	9.59E-03
	Adult	2.28E-05	1.30E-03	1.83E-03	9.27E-03	8.26E-04
Yam	*Child*	4.37E-05	2.20E-03	2.57E-02	1.55E-02	3.26E-03
	Adult	2.81E-05	1.41E-03	1.98E-03	9.95E-03	8.95E-04

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.0 Conclusion

The study found that eating food crops such as cassava, cocoyam, and yam exposed Mampong residents to natural radioactivity and heavy metals (Pb, Ni, Cd, Cu, As, Cr, and Zn).

All the metals under study had average concentrations in Mampong soils within the allowable limits established by CCME and VROM, with the exception of Cd, which had a greater concentration. Once more, the quantities of the metals under study in the different food crops—cassava, cocoyam, and yam were all within the WHO/FAO-established tolerable limits; however, the amounts of Cd and Cr were much higher. The risk assessment for human health, both carcinogenic and non-carcinogenic, was computed. With the exception of the Zn, Cr, Cd, and Mn HQ values in cocoyam, which were over 1, the majority of the HQ values determined from the root tubers in the tested community (Mampong) were found to be below 1 for both adults and children. This implies that eating these root tubers may have a somewhat negative impact on the people of Mampong. When calculating the hazard quotient to assess the non-carcinogenic health risk associated with consuming cassava, cocoyam, and yam, the total hazard quotient was found to be less than 1, indicating that the current exposure levels do not pose a significant health risk to the population.

Compared to ^{238}U and ^{232}Th, the activity concentration of ^{40}K in food crops was found to be much greater. The geological features of the research region affected the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in the soils. The UNSCEAR 2000 permitted limit of 30 Bq/kg, 35 Bq/kg, and 400 Bq/kg was exceeded by the activity concentrations of ^{238}U (97.14 Bq/kg), ^{232}Th (240.18 Bq/kg), and ^{40}K (191.18 Bq/kg), respectively. The study community's average external hazard index was more than unity, suggesting that the population is exposed to gamma radiation from the soils under research on an external level. Residents of Mampong get an average of 0.24 ± 0.06 mSv/y annually, which is under the 0.3 mSv/y safe range that is advised (UNSCEAR 2000). All the calculated increased lifetime cancer risk values were below the predetermined threshold of 0.0029 Sv^{-1} (UNSCEAR 2000). This suggests that there is no chance of cancer forming throughout the lifespan of those exposed to this radiation.

In order to determine the levels of radioactivity and metal concentrations to which the population is exposed, as well as to provide baseline data for future research, it is intended that the findings of this study will be a valuable source of information for future investigations in other regions of the nation.

5.2 Recommendation

The study's conclusions highlight the necessity of taking preventative action against heavy metal and naturally occurring radioactive material (NORM) contamination of food crops and agricultural soils in the Mampong Municipality. First, it's crucial to set up regular monitoring procedures. Regulatory authorities such as the Environmental Protection Agency (EPA), the Ghana Standards Authority (GSA), the Food and Drugs Authority (FDA), and the Ghana Atomic Energy Commission (GAEC) should implement routine testing of soil, water, and crops for NORMs and heavy metals. This would enable them to identify hotspots, analyze contamination trends over time, and assess seasonal or environmental changes that might impact contaminant distribution.

Such information would facilitate prompt and well-informed decision-making, especially in regions undergoing industrial or agricultural expansion.

To lessen the concentrations of heavy metals that plants absorb, soil and crop management techniques should be used. Adjusting soil pH, adding more organic matter, and applying amendments that immobilize metals might decrease their bioavailability to crops because it has been demonstrated that metals like cadmium and chromium concentrate in edible sections of crops, particularly cocoyam. With the right direction, local farmers may use these reasonably priced methods, which will reduce the amount of toxins that enter the food chain.

To control pollutant levels, stricter enforcement and regulatory criteria are required. Institutions such as the EPA, GSA, FDA, and GAEC should ensure that existing standards are reviewed and updated to account for NORMs and heavy metals in soil, water, and food, incorporating current contamination data. Public health protection depends on the effective execution of these regulations, particularly in areas close to industrial sites or where pesticides and fertilizers are widely used.

Furthermore, encouraging the prudent and safe application of pesticides and fertilizers would aid in reducing the metal concentrations that are introduced into the soil. When feasible, farmers should be encouraged to use organic fertilisers or fertilisers devoid of heavy metals, and they should be trained in the safe administration of chemical inputs. This change may promote healthy crop output and lessen long-term soil pollution.

Programs for health education and public awareness should be increased to educate locals about the possible health hazards associated with polluted crops. Agencies such as the Ghana Health Service (GHS), the Ministry of Food and Agriculture (MoFA), and local municipal health departments should spearhead initiatives to raise awareness, particularly for vulnerable populations like children, who are more susceptible to metal poisoning. Community-based programs can educate residents on healthy eating habits and encourage dietary diversity to mitigate exposure risks.

It would be advantageous to conduct further research on efficient soil remediation methods like soil washing and phytoremediation. These techniques have the potential to lower soil contamination levels, but further study is needed to determine which are most practical given the local circumstances. Furthermore, research on the combined impacts of heavy metals and NORMs on ecosystems and human health will help to clarify concerns and guide targeted solutions.

Lastly, it is critical that policies promote sustainable farming methods. The Ministry of Environment, Science, Technology, and Innovation (MESTI) and MoFA should advocate for environmentally friendly agricultural practices such as crop rotation, organic farming, and water conservation. These methods not only preserve environmental resources but also promote long-term agricultural productivity and food safety, particularly in areas like Mampong Municipality.

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