AKENTEN APPIAH-MENKA UNIVERSITY OF SKILLS TRAINING AND ENTREPRENEURIAL DEVELOPMENT

ASSESSMENT OF NATURAL RADIONUCLIDE CONTENTS IN LOCAL AND IMPORTED RICE SOLD IN TAMALE METROPOLIS AND THEIR HEALTH EFFECTS ON CONSUMERS

NUNIFANT KONLAN TIMOTHY

JUNE, 2024

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BY

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A thesis submitted to the School of Graduate Studies, Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development in partial fulfillment of the requirements for the award of a Master of Philosophy degree in Chemistry Education

JUNE, 2024

DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original work and that no part of it has been presented for another degree at this university or elsewhere.

Nunifant Konlan Timothy

Signature:……. Date:…..……

Supervisors' 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 Appia-Menka University of Skills and Entrepreneurial Development.

Dr Emmanuel Agyapong Asare (Principal Supervisor)

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ABSTRACT

This study determined the concentrations of natural radionuclides in locally grown and imported rice sold in Tamale metropolis using gamma ray spectrometry with a High Purity Germanium (HPGe) Detector. Eight samples (four local and four imported samples) were bought from Tamale Central and Aboabo markets and used for the analysis. In the local rice, the mean activity concentrations of Ra-226, Th-228, Ra-228, Th-232 and K-40 were 2.5 ± 0.19, 0.7 ± 0.08, 3.8 ±0.40, 4.28 ± 0.34 and 49.73 ± 3.99 Bq/kg respectively, while in the imported rice, the mean activity concentrations were 2.13 ±0.23, 1.28 ± 0.09, 4.2 ± 0.34, 1.7 ± 0.11 and 27.33 ± 2.24 Bq/kg respectively. These levels were below World average values as per UNSCEAR (2000). Comparison of the concentrations of radionuclides detected in the local and imported rice samples showed that there were no significant differences in their mean concentrations. The mean values of external and internal hazard indices for local rice were 0.0336 and 0.0404 respectively while those for imported rice were 0.0180 and 0.0237 respectively. The mean values were below unity. These indicate that the rice samples (both local and imported) are not hazardous to consumers. The mean values of Excess Lifetime Cancer Risk for the local and imported rice samples were 0.0295 x 10^{-3} and 0.0160 x 10^{-3} respectively. These values are below the world average value of 0.29×10^{-3}. The results suggest that both local and imported rice sold in Tamale metropolis are radiologically safe for consumers. Continuous monitoring in each production season, similar studies in rice produced in other parts of the country and similar studies in tuber crops were recommended.

ACKNOWLEDGEMENT

First and foremost, I thank the Lord Almighty for the protection and direction that made it possible that I get this far.

I am highly indebted to my supervisor, Dr Emmanuel Agyapong Asare for supervising this work. I am really glad for all the technical assistance, guidance and encouragement. You were always available for me. God richly bless you.

I am also grateful to Dr. Oscar Adukpo and all members of staff of the Radiation Protection Unit of the Ghana Atomic Energy Commission (G.A.E.C) for all the technical assistance offered during the analysis. I also wish to express my sincere gratitude to Mr. Kwame Duut for his assistance whenever I am in Asante Mampong for this work. Last but not the least, I must also express my gratitude to my wife, madam Diana Jabituk for the support and co-operation throughout the programme.

DEDICATION

I dedicate this thesis to my late father, Chief Nunifant Konlan for his love and support towards my education.

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ABBREVIATIONS

ATSDR	Agency for Toxic Substances and Disease Registry
CEC	Commission of the European Communities
CNCAN	National Commission for Nuclear Activities Control
ELCR	Excess Lifetime Cancer Risk
AEDE	Annual Effective Dose Equivalent
AGDE	Annual gonadal dose equivalent
DL	Duration of life/average life expectancy
RF	Risk factor (S/v)
FAO	Food and Agriculture Organization of the United Nations
GSS	Ghana Statistical Service
HPGe	High Purity Germanium
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
MDA	Minimum Detectable Activity
NEA	Nuclear Energy Agency of OECD
NORM	Naturally Occurring Radioactive Materials
OECD	Organisation for Economic Co-operation and Development
TAMA	Tamale Metropolitan Assembly
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USNRC	United States Nuclear Regulatory Commission
WHO	World Health Organization

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Radionuclides are unstable isotopes that undergo radioactive decay to release gamma rays, beta particles, and/or alpha particles (Carlsson, 2022; Taj, 2022). Natural radionuclides are radionuclides which arise from natural sources (Carlsson, 2022). They undergo spontaneous radioactive decay to emit radiations (Ojovan & Lee, 2005; Ehsan et al., 2019).

Radionuclides that occur naturally can be classified into three types: primordial, secondary, and cosmogenic (Kong et al., 2022; Melintescu, 2010). Radionuclides classified as primordial have half-lives that are significantly longer than the age of the earth (Duarte et al., 2023). They originate mainly from the interiors of stars through a phenomenon called nucleosynthesis. Examples of primordial radionuclides include isotopes of potassium (K-40), uranium (U-238), thorium (Th-232), etc (Saadi et al., 2022). Because these naturally occurring radioactive materials (NORM) have long half-lives and have not completely decayed, they can still be found in environmental samples (Kong et al., 2022; Melintescu, 2010). The radiogenic isotopes known as secondary radionuclides are produced when primordial radionuclides decay (García-León, 2022). Examples of secondary radionuclides are: thorium-234 (formed from alpha decay of uranium-238), Protactinium-234 (formed from beta-decay of thorium-234), among others (García-León, 2022). The radiogenic isotopes known as

secondary radionuclides are produced when primordial radionuclides decay (Kong et al., 2022; Melintescu, 2010).

When cosmic rays from stars, particularly the Sun, combine with the oxygen and nitrogen nuclei in the atmosphere, they produce cosmogenic radionuclides (Wieler, 2023). Because cosmic rays cause these cosmogenic radionuclides to continuously form in the atmosphere, they are present in the atmosphere at all times (Biswas et al., 2023). With the exception of tritium (H-3) and carbon-14 (C-14), which have half-lives of 12.3 years and 14 years, respectively, the majority of cosmogenic radionuclides have very short half-lives. Cosmogenic radionuclides have short half-lives, but they are found in nature because their supply is constantly renewed (Wieler, 2023). Examples of cosmogenic radionuclides include C-14, H-3 and beryllium-7 (Be-7) (Alrefae, 2012; Alrefae et al., 2012; Kovler, 2012).

Humans and the environment are constantly subjected to background radiation from naturally occurring radionuclides, in addition to medical exposures (diagnostic and therapeutic exposures), nuclear tests, and accidents (Vaiserman et al., 2021). Compared to man-made radionuclides, NORM contribute significantly more to doses (Strumińska-Parulska & Falandysz, 2020). It has recently become clear that one of the causes of natural exposure is inhaling the short-lived decay products of Rn-222 (Desouky et al., 2015; IAEA, 2019).

Natural radionuclides occur in all types of food (Jayasinghe et al., 2020). Natural radionuclides can again be transferred into food in different ways. For example, weathering of the earth crust can release primordial radionuclides into the soil. Plants

absorb radioactive elements from the soil through their roots or leaves (Aba, Ismaeel & Al-Boloushi, 2021; Rzabay et al., 2022). When crops grown from these soil are ingested, ionizing radiations can enter the body and transfer these radionuclides to humans. Radionuclides in air can settle onto crops (Rzabay et al., 2022). Humans are exposed to these radionuclides when they consume the crops.

Human exposure to radionuclides can also be through bioaccumulation (Leaphart, et al., 2022). Radionuclides may also accumulate in farm animals through the consumption of plants, phosphate-based mineral feed supplements or water containing radioactive materials, which can subsequently be transferred to humans when consumed (Alharbi and El-Taber, 2013; Adesiji and Ademola, 2019).

According to Olatunji et al. (2022) anthropogenic radionuclides can potentially contaminate food. This occurs when radioactive elements leak into the environment as a result of nuclear accidents and civil or military nuclear operations including testing nuclear weapons (Bolton & Minor, 2021). According to Rzabay et al. (2022) artificial radiation can then move up the food chain in the same manner as natural radioactivity.

Terrestrial and aquatic food chains contain both naturally occurring and man-made radionuclides (Salminen-Paatero & Paatero, 2021). They can then be carried across to humans by eating certain foods. The main radiation channels for long-term health concerns include foodstuffs that contain radionuclides. These radionuclides greatly increase the average radiation exposures to the body's tissues and organs (IAEA, 2019; Jibiri et al., 2007). As a result, radiation exposure from food consumption by humans is of global interest (Ababneh et al., 2010; Alrefae et al., 2012).

Exposure to radionuclides in food originates from two routes, viz: external and internal exposure. There is an internal exposure to alpha particles due to the decay of radon-222 (Rn-222) and its progeny, which are decay products with short half-lives. Radon is a chemically inert, colourless, odourless, and extremely radioactive gas. The tissue in the bronchi instantly absorbs the dose of alpha particles from radon. This makes radiogenic lung cancer probable (Kovler, 2012).

Additionally, direct gamma radiation from the decay of K-40, radionuclides of the Th-232, and U-238 series is the main source of external exposure. The most significant decay chain in the U-238 series begins with radium Ra-226. For this reason, the U-238 chain is frequently called the Ra-226 chain (Kovler, 2012).

After maize, rice is the second most important staple in Ghana (Danso-Abbeam et al., 2014). Beginning in 1957, the early post-independence era saw a sharp shift in diet, mostly in urban areas, toward rice. Ankrah et al. (2022) ascribed the shift to factors such as elevated income, advantageous government pricing regulations, superior rice storability, and effortless cooking. Between 2007 and 2016, the yearly area planted to rice climbed to 236,000 ha (MoFA, 2017). In 2016, the volume of production rose from 185,000 Mt to 688,000 Mt. According to Abukari et al. (2019), the production of rice in Ghana is high in the Volta, Northern, Upper East, Eastern and Ashanti regions. The majority producer, with over 63 000 tons produced in 2009, is the northern region (MoFA, 2019).

Ghana uses roughly 1.5 million metric tonnes of rice annually (MoFA, 2023). At the moment, the nation produces enough to meet around half of its demand (MoFA,

2023). Due to its ease of preparation, rice is frequently consumed in large quantities during events like weddings, naming ceremonies, funerals, etc.

Imported rice has a social prestige associated with it. Rice from imports has higher processing quality, which makes them whiter. Their prices are higher as a result of this perceived excellence. Long grain aromatic cultivars, which are primarily imported, are preferred by households in both rural and urban areas (Angelucci et al., 2013). While local rice consumption is higher in the rural areas due to availability and affordability, the majority of imported rice is consumed in metropolitan areas (Abukari et al., 2019).

Because local rice is considered to be of poorer quality because of inadequate harvesting and milling techniques, it is priced lower (Abukari et al., 2019). The entire stem is chopped and the grain is only loosely separated in the Tamale region, where the majority of rice is harvested by hand. The processed rice that is left behind is really filthy and dark brown. Consequently, low-income people are the primary consumers of local rice, particularly in rural regions (Abukari et al., 2019). The socioeconomic division between people who purchase local rice varieties and those who purchase imported rice is reflected in cost differences. This has been so ingrained that when the price of imported rice rises due to currency fluctuations, there may not always be a significant demand for local rice. Though in lesser amounts, those who have a predilection for imported rice nevertheless buy it (Abukari et al., 2019).

Rice is one of the commonly consumed foods in Tamale metropolis (Angelucci et al., 2013). It is used for a wide range of food products such as jollof rice, rice balls

(Sinkafa kpila), rice and beans cooked together (popularly known as waakye), fried rice, plain rice with stew and rice water. Market survey by the researcher shows that the common types of rice sold in Tamale central and Aboaba markets include Texas star rice (imported from USA), USA rice (imported form the USA), Cindy jasmine rice (imported from Vietnam), Royal Aroma rice (imported from Vietnam), Nasia rice (produced at Nasia), Bolga rice (produced in Bolga), Tamale (Dagbamba) rice and Royal Farmers rice (produced in Nyankpala, Tamale).

1.2 Statement of the Problem

Naturally occurring radionuclides such as K-40, U-238, Ra-226 and their decay products are present in all foods but their levels are usually very low and safe for human consumption. However, the levels can reach unsafe limits due to the local geology, climate and agricultural practices. When this happens, the food can pose health risk to humans who consume them (Onjefu et al., 2020).

Food that contains high radioactive contamination levels might build up in specific bodily areas. For instance, the human kidney and lungs can accumulate U-238 and Ra-226, the human liver, bones, tissue, and lungs can accumulate Th-232, and the human muscles can accumulate K-40 (Tawalbeh et al., 2012). The buildup of these radionuclides in any of the body's essential organs can have an impact on health, including a weakened immune system, mutagenic effects on humans, leukemia, cataracts in the eyes, cancer of many kinds, genetic abnormalities, somatic destruction and a higher death rate (Adeniji et al., 2013). The risk is most when contaminated food, water, or air is consumed and the radionuclide enters the body (UNSCEAR, 2000). Consequently, there is concern about human radiation exposure worldwide

because radionuclides can be ingested through food, drink, and the air (IAEA, 1989 as cited in Alrefae & Nageswaran, 2013).

1.3 Objectives of the Study

The purpose of this study is to evaluate the levels of natural radionuclides in local and imported rice sold in Tamale metropolis and to assess their effects on human health.

Specific objectives of this study are to:

1. determine concentrations of natural radionuclides in local and imported rice sold in Tamale Metropolis in Ghana
2. compare levels of natural radionuclides in local and imported rice sold in Tamale metropolis.
3. determine possible risk associated with consumption of local and imported rice sold in Tamale metropolis.

1.4 Significance of the Study

Rice is a stable food for inhabitants of Tamale metropolis (Danso-Abbeam et al., 2014). Due to health risk associated with radionuclides in food, it is essential to establish their levels in foods regularly consumed. Though a lot of studies have been done on levels of radionuclides in rice across the world (Younis & Tawfiq, 2019; Najam et al., 2015), none has focused specifically on radionuclide levels in local and imported rice sold in the Tamale metropolis. Therefore, the findings of this study will help determine radioactivity levels and radiological safety of rice consumed in Tamale metropolis. This will be beneficial to consumers of rice. Furthermore, the research findings will also add modern analytical data to the national and global data on radioactivity levels of rice.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter gives the background information about natural radionuclides, the three natural radioactive decay series, effects of radiation, rice production, trade and a review of previous studies on radioactivity of rice and other foodstuffs.

2.2 Natural Radionuclides

This study targets natural radionuclides (radium-226, thorium-228, radium-228, thorium-232 and potassium-40) in rice sold in Tamale metropolis. The lengthy half-lives of these radionuclides are equivalent to the age of the earth (Resdi et al., 2021).

The worldwide environment contains significant concentrations of naturally occurring radionuclides and their decay products (Ahmed, 2021). Gamma radiation is the primary form of external radionuclide exposure that affects human body (Abojassim & Rasheed, 2021). These radionuclides are also present in the human body and emit gamma rays, alpha particles, and beta particles into the different organs (Reddy et al., 2020).

2.2.1 Uranium (U)

Rocks, soils and water all contain uranium, a radioactive metal that occurs naturally. U decays by alpha particle emission. Due to geological deposits and geochemical

processes, it is typical in the natural world (Vodyanitskii, 2011; Bjorklund et al., 2020).

In the earth's crust, the abundance of uranium is 2.3 μg g^{-1} (Vodyanitskii, 2011). Natural uranium contains three main isotopes, all of which are radioactive. These are: Uranium-234 (U-234) which makes up 0.0055%, uranium-235 (U-235) which makes up 0.7200%, and uranium-238 (U-238) which makes up 99.2745%. The half-lives of these isotopes are: 2.455×10^5, 7.038×10^8, and 4.468×10^9 years respectively (Bjorklund et al., 2020). The two most abundant isotopes (U-235 and U-235) have existed since the Earth's creation (Al-Full & Khattab, 2022). Due to these radioisotopes' extended half-lives, U's radioactivity is incredibly low in the natural world (Al-Full & Khattab, 2022). Furthermore, human activities like farming and mining can change the geologic distribution of uranium and cause environmental uranium leakage (Balaram et al., 2022). Accordingly, there is a growing risk to the public's health due to uranium pollution from both man-made and natural sources (O'Connor et al., 2014).

In aqueous solutions, uranium exists in two distinct ion states: tetravalent in reducing environments and hexavalent in oxidizing environments. Tetravalent uranium is not very soluble in reducing circumstances; instead, it tends to precipitate out or sorb to adjacent minerals or organic molecules. According to Westrop et al. (2023), because bicarbonate and other anions are present, uranium becomes moderately soluble in oxidizing conditions. The atomic size, valence, and electronegativity of uranium are all quite big. Since uranium cannot form isomorphic series including primary minerals that form rocks, such as quartz or feldspar, when an igneous rock crystallizes from a

magma, it is primarily present in accessory minerals (Damdinov et al., 2022). The accessory minerals xenotime, apatite, sphene, zircon, allanite, monazite, pyrochlore, and uraninite are frequently discovered to contain uranium. Due to its solubility in oxidizing aqueous solutions, uranium exhibits high mobility in geologic materials found on and near the surface. As a result, surface uranium concentrations frequently fluctuate more than thorium or potassium concentrations (USGS, 2004; Nimmo et al., 2020).

Lead-206 (Pb-206) is the result of the disintegration of U-238 through a sequence of processes. The production of radon gas (Rn-222) from the radioactive decay of U-238 results in the production of polonium-210 (Po-210) and lead-210 (Pb-210), which when inhaled greatly increase the total dose. Due to their comparatively lengthy half-lives 22 years for Pb-210 and 140 days for Po-210 both radionuclides are found in nature, albeit in extremely small amounts (trace) (Carvalho et al., 2017). Ingestion is the primary method of Pb-210 and Po-210 exposure (Wang et al., 2022). Po-210's presence in food accounts for the majority of the ingested dosage from the U-238 series. Due to Pb-210's lengthy half-life in the human body, notably in the bones, it also considerably increases the population's overall radiation exposure (O'Connor et al., 2014).

Although uranium's radiotoxicity has received a lot of attention, the primary concern of uranium exposure in the environment is believed to be its chemotoxicity as a heavy metal. This is dependent upon the exposure route, enrichment grade, and chemical species (Canu et al., 2011).

Uranium contamination is a result of mining (41.14%), groundwater (39.67%), fertilizer (7.57%), nuclear facilities (7.25%) and the military (4.36%). Humans are mostly exposed to uranium naturally through the consumption of food and water (UNSCEAR, 2016; Padhi et al., 2023).

The uranium and thorium series radionuclides' average yearly individual exposure in the general population's entire diet (food and drinking water combined) is 0.12mSv (UNSCEAR, 2008).

Every type of rock and soil contains uranium. According to activity concentrations for U-238 of 7–60 Bq/kg (0.2–1.6 pCi/g), uranium concentrations in typical rock types range from 0.5 to 4.7 ppm (Mwalongo et al., 2023). The average concentration of uranium in soil is lower than the average concentration in rock as a result of the overall influence of soil development. Radionuclide concentrations in residues produced during the mining and processing of some ores for nonradioactive minerals can be increased. One famous example is phosphorus ore, which has been exploited as a commercial source of uranium and contains up to 120 parts per million of uranium. Uranium ores are defined as naturally occurring materials with uranium concentrations greater than 500 ppm (Afifi, 2021).

According to Pillai (2019) and Balaram et al. (2022) uranium can also be found in food, drink, and air. As a result, it is present in human tissues. Every year, around 13 Bq (350 pCi) of uranium are consumed through diet (Pillai, 2019). According to Sahoo et al. (2021), the amount of uranium ingested from tap water may constitute a minor or major portion of the overall intake, contingent upon the concentrations in

various local water sources. The average uranium concentration in the US skeleton (wet weight) is around 8 mBq/kg (0.2 pCi/kg) (Golden et al., 2021). According to estimates from Golden et al. (2021) and Zhang et al. (2022), US inhabitants receive the largest yearly doses of radiation from uranium in their lung, kidney, and bone, which are 11, 9.2, and 6.4 μSv (1.1, 0.92, and 0.64 mrem), respectively.

The danger that uranium poses to humans from exposures both within and outside of the body is greater for radium and other decay products of uranium than for uranium itself (Tirmarche et al., 2021).

2.2.2 Radium (Ra)

Radium-228 (Ra-228) is a radioactive decay product in the thorium-232 (Th-232) decay series, and most of the dose attributed to Th-232 is in fact produced by Ra-228 (O'Connor et al., 2014). Th-232 is present in the crust of the Earth and is, on average, three times more prevalent than lead and uranium (Faweya et al., 2023). Lead-208 (Pb-208) is the stable decay product of Th-232. Typically, volcanic rocks like granites have the highest thorium contents, whereas carbonate rocks like limestones have the lowest amounts (Siegesmund et al., 2022).

In the uranium-238 (U-238) decay chain, radium-226 (Ra-226) is a radioactive decay product that precedes radon-222 (Rn-222). Radium can enter the body through the natural contents of food, drink, and dust particles dispersed in the atmosphere. The majority of radium ingested (about 80%) will quickly exit the body through feces (Tasev et al., 2021). The remaining components (20%) are transported throughout the body by the bloodstream. Radium and calcium have comparable metabolic patterns in

the body. As a result, teeth and bone receive a sizable portion of the deposit more frequently. Although it is typically not a substantial source, the body can also manufacture radium from its parent radionuclide, uranium, if it is ingested or inhaled (O'Connor et al., 2014).

It can remain in the lungs for three months if radium is breathed in. Every portion of the body will gradually absorb it as it permeates the blood. According to Bartlett (2022), the bones will be most impacted. The body will excrete every tiny amount through waste products and urine for several months following exposure. Most radium will swiftly exit the body as waste matter if it is ingested in water or food. Certain particles will infiltrate the bloodstream and travel throughout the body, primarily to the solid tissues. Daily excretions of waste products will remove little amounts from the body (Bartlett, 2022).

Radium is found in nature at low concentrations. Extended exposure to low concentrations is not detrimental, according to any data (Fernando et al., 2022). Long-term exposure to elevated radium levels can result in death and other serious health issues (Peana et al., 2021). Elevated radium levels have been linked to several health problems, including cancer (particularly bone cancer), anemia, blood disorders, dental fractures, cavities, and cataract growths (Peana et al., 2021). It takes years for some of these health issues to manifest. The majority are caused by gamma radiation, which is airborne and has a large range (Martinez et al., 2022). Dangerous quantities of radium can be found just nearby. One recognized chemical that causes cancer is radium. Increased risk of breast, liver, and bone cancer can result from high radiation exposure (Peart, 2017).

2.2.3 Potassium-40 (K-40)

In the Earth's crust, potassium ranks seventh in terms of abundance, but in oceanic solutions, it ranks sixth (Alvin et al., 2020). Three isotopes of potassium are found in nature: potassium-39, potassium-40, and potassium-41. Only potassium-40, the least abundant of the three isotopes, is radioactive (Jha et al., 2021). K-40 has a half-life of 1.3 billion years (ZA et al., 2021). It decays by emitting beta particles into calcium-40 (89%) and absorbing electrons to form argon-40 (11%), whereupon it emits 1.46 MeV gamma rays upon electron capture (Karmaker et al., 2021).

Potassium is a vital component of soil that is found in all plant and animal tissues and is widely dispersed throughout nature (O'Connor et al., 2014). Potassium-40 poses a risk to internal and exterior health (Hassan et al., 2022). The strong gamma radiation this isotope emits causes external exposure. Because of the beta particles and gamma radiation it emits when within the body, potassium-40 is harmful (Adel et al., 2022; Saleh et al., 2022). Potassium-40 poses a health risk due to the ionizing radiation it releases during radioactive decay, which can harm cells and increase the risk of cancer (Panera et al., 2021).

Humans need potassium to support biological activities, and potassium-40 can enter the body through food, drink, or air (Wojtkowska et al., 2022). Once within the body, potassium-40 functions similarly to other potassium isotopes (Salama & Mohammed, 2023). Upon consumption, most of the potassium (including potassium-40) becomes virtually entirely absorbed and travels swiftly from the gastrointestinal system to the circulation (Altıkulaç et al., 2015). Upon consumption or inhalation, potassium-40 enters the bloodstream and is rapidly disseminated throughout all organs and tissues

(Altıkulaç et al., 2015). Potassium-40 is eliminated from the body with a biological half-life of 30 days (Altıkulaç et al., 2015; Mosher & Kelter, 2023).

The body always contains potassium-40; an adult male has approximately 0.1 microcurie (μCi). This isotope supplies doses of roughly 18 millirem (mrem) to the body's soft tissues and 14 mrem to bone annually (Külahcı & Çiçek, 2019).

Ionizing radiation produced by potassium breaks DNA, causes defective or effective repair, causes apoptosis, chromosomal damage, gene mutations, and genetic instability (Mohan & Chopra, 2022; Orosun et al., 2017). Normal tissue and cell equilibrium is lost as a result, and cancerous growth results. Like other potassium isotopes, potassium-40 functions in the body in a similar way. After consumption, potassium enters the bloodstream swiftly after being virtually entirely absorbed in the gastrointestinal tract. After being consumed or inhaled, potassium-40 enters the bloodstream and swiftly permeates all tissues and organs. Potassium-40 poses a permanent risk to interior health. External exposure to this isotope is dangerous due to the intense gamma radiation (Geelen, et al., 2022). Both gamma radiation and beta particles present a health risk when potassium-40 is within the body. Potassium-40 poses a health risk due to its association with ionizing radiation, which is produced by radioactive decay and can induce cell damage and subsequent cancer formation.

The symptoms of acute radiation syndrome, which can result from high doses of ionizing radiation exposure, include fever, skin burns, hair loss, nausea, vomiting, low blood pressure, headaches, fatigue, weakness, and birth abnormalities (Stenke et al., 2022).

2.2.4 Thorium (Th)

Natural radioactive elements such as thorium can be found in trace amounts in rocks, soil, water, plants, and animals (Asare, 2021). Radiation-emitting isotopes thorium-232, thorium-230, or thorium-228 comprise nearly all naturally occurring thorium (Ahmadov et al., 2016; ATSDR, 2019). Compared to uranium, thorium is more common. It is thought that thorium makes up three to four times more of the crust of the planet than uranium does (Hania & Klaassen, 2012; Putri et al., 2022).

Due to its enormous atomic size, high valence, and strong electronegativity, thorium is unable to construct isomorphic series including the main minerals that compose rocks (Ratnayake et al., 2023). Consequently, auxiliary minerals are where it is most common. In the tetravalent state, thorium is stable under oxidizing circumstances and insoluble in aqueous solutions. Thorite, pyrochlore, zircon, apatite, sphene, zircon, allanite, monazite, and xenotime are a few accessory minerals that frequently include thorium (USGS, 2004; Björk et al., 2022).

Gamma radiation, alpha and beta particles, and other radiation are released during the decay of thorium-232 and its decay products (Joel et al., 2021). Since thorium-232 has an extremely long half-life of almost 14 billion years, it decays more slowly than other isotopes of thorium (Supriadi et al., 2020; Rump et al., 2023). The natural quantity of thorium in the earth is nearly constant because of this slow rate of disintegration, although both natural and human activity can cause it to migrate (US EPA, 2014; Lecomte et al., 2019).

As thorium is a naturally occurring element in the environment, humans may be exposed to trace amounts of it in their food, water, and air (Desouky, 2021). Usually in extremely small doses, there is little risk to health.

Additionally, thorium can be found in a lot of consumer goods like welding rods, lantern mantles, and ceramic glazes (Hassan et al., 2021). Living close to thorium mining, milling, or product manufacturing facilities may result in increased exposure (Brown, 2021). Additionally, there may be increased exposure for those who work with thorium in a variety of industries (Brown, 2021).

Individuals might ingest thorium through food or drink or breathe in polluted dust. As a result, your risk of being exposed to thorium increases if you live close to a site that has been contaminated by thorium or work in an industry that uses thorium (Vural, 2019). Some thorium, when inhaled as dust, can remain in the lungs for long periods of time depending on its chemical state (Kamalakar et al., 2022). Thorium usually exits the body through urine and feces in a few days if it is consumed (Kamalakar et al., 2022). The residual tiny quantity of thorium in the body will travel through the circulation and settle in the bones, where it might stay for a very long time (Kamalakar et al., 2022).

Though there is some evidence that the skin could be the main route of entrance, the body could potentially absorb thorium that way (Mohan & Chopra, 2022). Increased risk is the main worry with radiation exposure at low to moderate levels. Research has indicated that breathing in thorium increases the risk of lung cancer and pancreatic cancer (Grzywa-Celińska et al., 2020).

2.3 Sources of Natural Radionuclides

Ionizing radiation is constantly present in all living things since it comes from natural sources (Vaiserman et al., 2021). The exposure levels differ according on height and location (Mitrović et al., 2020). The main sources of natural radionuclides are: terrestrial radionuclides and cosmogenic radionuclides.

2.3.1 Terrestrial Radionuclides

Terrestrial radionuclides are those found in the earth itself. For example, radionuclides present in the soil, rocks, water, soil, air, coal, etc (Ujjinappa, et al., 2021). Primary radionuclides are those that have been on the planet since its formation and secondary radionuclides that are produced when long-lived radionuclides like radon decay. They also include those radionuclides with extremely long half-lives (100 million years or more) (Karanggulimu & Harefa, 2022). The following are some examples: Th-232 has a half-life of 1.41 × 1010 years, U-238 has a half-life of 4.47 x 109 years, and K-40 has a half-life of 1.28 x 109 years. Rb-87, with a half-life of 4.70 × 1010 years, and U-235, with a half-life of 7.04 x 108 years, are two other primordial radionuclides of secondary relevance. The two most common radionuclides among them are uranium and thorium, both of which increase the amount of radiation that is exposed to by humans (Thakur et al., 2022).

Numerous industrial operations unrelated to the nuclear fuel cycle have the potential to expose workers and the general public to ionizing radiation (Taj, 2022). Since these sectors do not produce nuclear materials or utilize them due to their radioactive or nuclear characteristics, they are referred to as non-nuclear industries (Taj, 2022).

2.3.2 Cosmogenic Radionuclides

When cosmic rays impact with atoms in the atmosphere, they form cosmicgenic radionuclides, primarily carbon-14. Typically, they include: H-3, Be-7, C-14 and Na-22 (Golubenko et al., 2022). Cosmogenic radionuclides can also be formed by some protons and neutrons from cosmic rays that are strong enough to survive in the lower stratosphere, despite the fact that the production of these radionuclides is concentrated in the higher stratosphere (Schaefer et al., 2022). The projected yearly average effective dosage at sea level for the entire planet is 320μSv, of which 270μSv and 48μSv come from directly and indirectly ionizing radiation, respectively. Muons with energies ranging from 1 to 20 GeV make up the majority of the ground-level cosmic ray field and are responsible for around 80% of the absorbed dose rate in free air resulting from directly ionizing radiation (Durante & Manti, 2008). According to estimates, the directly ionizing and photon components of cosmic radiation at sea level have an average absorbed dose rate of 31 nGy/h (280 μSv/year), which is population-weighted (Durante & Manti, 2008). Because of the poor sensitivity of sensors to high energy photons, which make up the majority of the spectrum, measuring the neutron radiation component at sea level is more challenging. It is calculated that the annual average worldwide contribution of neutron components to cosmic radiation is 120 μSv. Durante and Manti (2008) estimate that almost half of the annual collective dosage which has a global value of approximately 2 x 106 man-Sv is received by two-thirds of the world's population who reside at an altitude of 0.5 km. The annual effective doses for C-14, Na-22, H-3, and Be-7 were reported to be 12 μSv, 0.15 μSv, and 0.01 μSv in earlier UNSCEAR reports about the evaluation of cosmogenic radionuclides. These cosmogenic radionuclides are rather evenly distributed across the earth's surface (Pitlick et al., 2021).

Table 2.1: Average radiation exposure from natural sources

Source	Worldwide average annual effective dose, mSv	Typical range
External		
Cosmic rays	0.4	0.3 – 1.0
Terrestrial rays	0.5	0.3 – 0.6
Internal		
Inhalation (radon)	1.2	0.2 – 10
Ingestion	0.3	0.2 – 0.8
Total	**2.4**	**1 – 10**

Source: Durante & Manti (2008).

In naturally occurring, undisturbed ecosystems, the natural radionuclides reside in secular equilibrium (Gocher et al., 2022). Radiation secular equilibrium of any series can be upset by physical-chemical processes occurring in the earth's crust, such as leaching and emission (Durante & Manti, 2008). According to studies conducted by Mahan et al. (2014), the mass ratio of U-235 to U-238 is around 0.0073, while the activity ratio is 0.046 under normal, undisturbed secular equilibrium conditions. When it comes to K-40, they go via beta decay to become stable species (Ca-40). These radionuclides are present in varying concentrations in soil, water, air, and living beings. As a result, radiation with varying energy ranges from gamma rays, beta particles, and alpha particles is exposed to humans both inside and externally (Schmid & Wakelam, 2020).

2.4 Man-made Sources

While natural background radiation is a part of life, persons who work in places where radiation is a concern or the general public are the two groups of people who are exposed to radiation from man-made sources (Cool et al., 2019).

2.4.1 Members of the Public

Public exposure to man-made radiation comes from the following sources:

- Tobacco processing
- Television
- Smoke detectors
- Lantern mantles
- Nuclear medicine
- Building materials.

(Cool et al., 2019; Akleyev et al., 2021; Chi, 2022).

Medical procedures including radiation therapy, nuclear medicine, and diagnostic x-rays are by far the biggest sources of man-made radiation exposure for the general public (Mettler Jr et al., 2020). I-131, Tc-99, Co-60, Ir-192, and Cs-137 are a few of the significant isotopes. In addition, building materials, combustible fuels (coal, gas, etc.), luminous watches and dials (tritium), tobacco (polonium-210), and ophthalmic glass televisions are among the consumer goods that expose people to radiation (Taj, 2022; Gaines et al., 2021). Additional ones are x-ray machines at airports, tungsten smoke detectors, materials used in road construction, electron tubes, starters for fluorescent lamps, and lantern mantles (thorium), etc (Vishwakarma et al., 2015).

Radiation exposure stems from the nuclear fuel cycle, which includes all steps in the process from mining and processing uranium to disposing of spent fuel at the end (Darda et al., 2021). These are byproducts of daughter uranium. Transportation and the residual effects of nuclear weapons testing and incidents like Chernobyl are the last ways that the general public is exposed to radioactive materials (Laine, 2022).

2.4.2 Occupationally Exposed Individuals

Occupationally exposed individuals work in the following environments:

- Industrial radiotherapy
- Radiology departments
- Nuclear power plant
- Nuclear medicine department
- National (government) and university research laboratories

(Boice et al., 2022; Abdelaziz et al., 2021; Getaldić et al., 2023; Senthilkumar et al., 2021).

Depending on their occupations and the sources they work with, people are exposed in different ways at work. Dosimeters are tiny devices that are used to precisely measure an individual's radiation exposure. Americium-241, cesim-137, cobalt-160, and other isotopes are among the ones that should be taken seriously (El-Benhawy et al., 2022).

2.5 Types of Radioactive Decay

2.5.1 Alpha (α) decay

α-decay involves the emission of two neutrons and two protons. Almost all naturally occurring elements with atomic numbers greater than 83 (Z > 83) are alpha particle emitters. Alpha decay can be represented by equation (1):

$$^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}X + {}^{4}_{2}He \qquad 1$$

Alpha particles cannot penetrate a sheet of paper or a dead layer of skin and so do not cause direct hazard to external body (Reeder & Taylor, 2019). However, inhalation or

ingestion of alpha particles could harm internal organs (Parrish & Seda, 2019). Examples of nuclides that decay by alpha particle emission are: $^{241}_{95}\mathrm{Am}$, $^{238}_{92}\mathrm{U}$ and $^{232}_{90}\mathrm{Th}$, etc.

2.5.2 Beta (β) Decay

β-decay is a type of radioactive decay characterized by the emission of electrons (β^-) or positrons (β^+) (Diehl, 2022). β^- or β^+ particles are faster, less ionization but more penetrating compared with alpha particles (Diehl, 2022). It only takes a few meters of air or an aluminum sheet to stop beta particles (β^- or β^+). Beta decay can be represented by the following equations (2 and 3) (Diehl, 2022):

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}X + {}^{0}_{-1}e + \text{-ve for } \beta^- \text{ (Electron emission)} \qquad 2$$

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}X + {}^{0}_{-1}e + \text{ve for } \beta^+ \text{ (Position emission)} \qquad 3$$

A positron, where -ve denotes an electron antineutrino and ve denotes an electron neutrino, has an electric charge that is opposite to that of an electron but has the same rest mass.

2.5.3 Gamma (γ) Decay

γ-decay is the term for the radioactive decay that happens when a nucleus moves from a higher energy level to a lower energy level. When alpha decay and beta decay occurs, the nucleus formed can be in the excited (high energy) state. The surplus energy is lost by the emission of gamma rays. Unlike alpha and beta decay, γ-decay does not produce a change in charge or mass. As extremely high frequency

electromagnetic radiation with high energy, gamma rays are not particles (wavelengths of 10^{-10} m).

Although the three forms of radiation are diverse in how they endanger human health, they are all fundamentally harmful because they lose energy when they travel through materials. Molecules can get ionized due to energy loss, and this can lead to further chemical processes in biological tissues. Cells may be destroyed as a result, or their roles may alter (Chancellor et al., 2018; Durante et al., 2019).

2.6 The Three Natural Radioactive Decay Series

Every naturally occurring isotope that has an atomic number higher than 83 decays radioactively through alpha or beta emissions. Furthermore, all of these naturally occurring heavy radionuclides fall into one of three decay series: uranium, actinium, or thorium. All three series involves a single gaseous component, an isotope of Rn, and concludes with a stable Pb isotope (USGS, 2004).

As the name suggests, the uranium series/chain (also called the radium series) starts with U-238. While Ra-226, the fifth daughter, decays into Rn-222, U-238 and its first five daughters stay solids in the soil. The noble gas that is this offspring, radon, is not chemically bonded to the substance that its parents lived in. A significant portion of the gas will be able to escape into the atmosphere during the 3.82-day half-life of Rn-222. In the other two series, radon is also produced. Nonetheless, these radon isotopes have little radiological significance (USGS, 2004).

The U-238 decay series emits gamma, beta, and alpha radiation. The key isotopes in the decay series are displayed in the Figure 2.1 below, together with the half-life and information on whether beta or alpha emission is the primary decay mode.

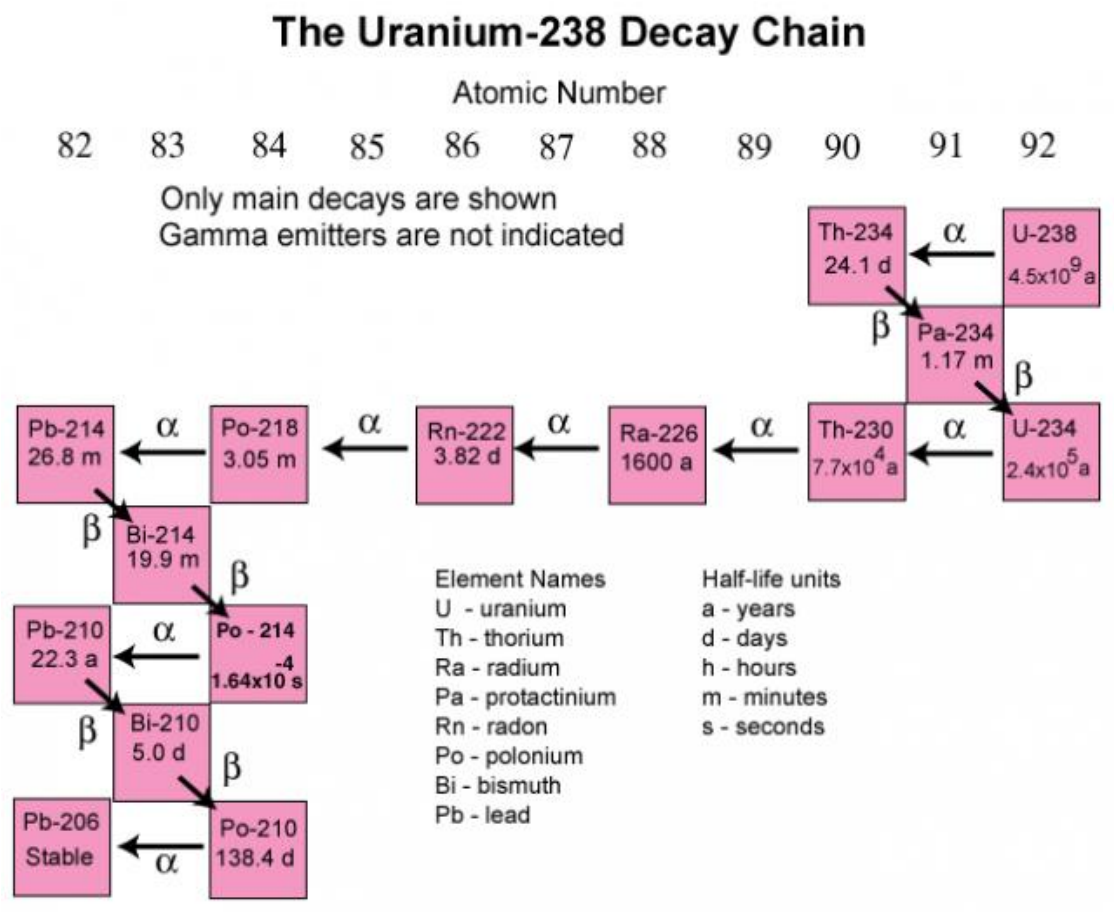

Figure 2.1: Uranium decay series

Source: USGS (2004)

The majority of daughter isotopes release gamma rays in addition to alpha or beta particles when their parent isotope decays. NaI(Tl) detectors are not suitable for use in gamma-ray spectrometry since the majority of gamma rays have energies less than 500 keV. There are gamma rays produced by Bi-214 that have energy higher than 1.0 MeV; the strongest of these gamma rays is listed in Table 2.2 below (USGS, 2004).

Table 2.2: Gamma rays produced by Bi-214 and their energies and relative intensities

Bi-214 gamma rays	
Gamma-ray energy (MeV)	Relative Intensity (percent)
1.12	15.1
1.16	1.6
1.24	5.8
1.28	1.4
1.38	4.0
1.40	1.3
1.41	2.2
1.51	2.1
1.66	1.2
1.76	15.4
1.85	2.1
2.12	1.1
2.20	5.1
2.45	1.6

Source: USGS (2004)

The majority of gamma-ray spectrometers used in geology assess the 1.76-MeV gamma-rays' intensity.

Th-232 is the starting point of the thorium series/chain, which leads to Rn-220, also known as thoron. Due to its 56-second a half-life, Rn-220 is far more likely to degrade before getting airborne.

The decay series of Th-232 results in radiation that is beta, gamma, and alpha. Figure 2.2 below lists the significant isotopes in the decay series, indicating whether beta or alpha emission is the primary decay mode, and provides the half-life.

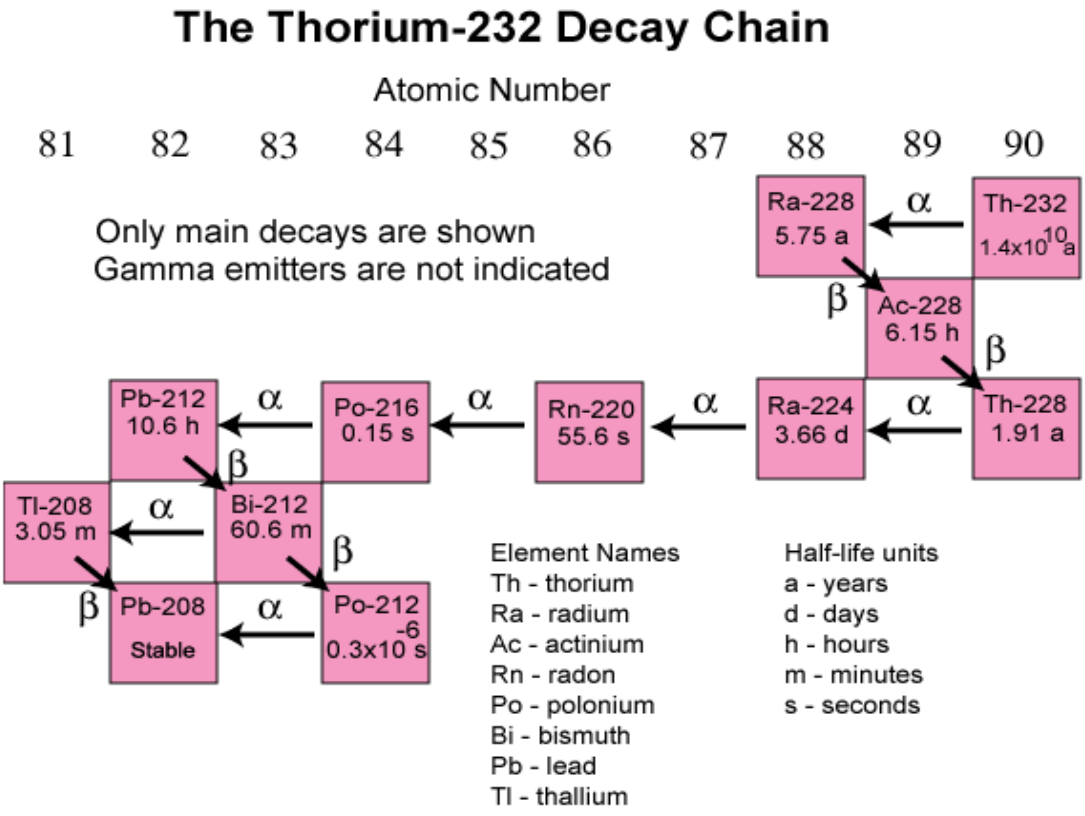

Figure 2.2: Thorium series

Source: USGS (2004)

The majority of daughter isotopes release gamma rays in addition to alpha or beta particles when their parent isotope decays. Their energy ranges from near zero to more than 2500 keV, although the majority of gamma rays have very low intensities and cannot be employed for gamma-ray spectrometry with NaI(Tl) detectors. The most powerful gamma rays produced by Tl-208 are listed in Table 2.3 below. Tl-208 does produce gamma rays with appropriate intensities (USGS, 2004).

Table 2.3: Gamma rays produced by Tl-208 and their energies and relative intensities

Tl-208 gamma rays	
Gamma-ray energy (MeV)	Relative Intensity (percent)
0.277	6.3
0.510	22.6
0.583	84.5
0.763	1.8
0.860	12.4
2.614	99.2

Source: USGS (2004)

The majority of gamma-ray spectrometers used in geology quantify the gamma-rays' intensity, which is measured in 2.614 MeV. Beginning with the comparatively uncommon U-235, the actinium series leads to Rn-219, commonly known as action (as shown in Figure 2.3). Actinon's contribution to airborne radon is negligible due to its short half-life of 4 s. Thus, from natural or artificial radioactive sources, Rn-222 (from Ra-226) and Rn-220 (from Ra-224), along with their short-lived decay products, are the main single contributors to human radiation exposure. For this reason, only radon found in the radium series is frequently taken into (Ishimori et al.,2013).

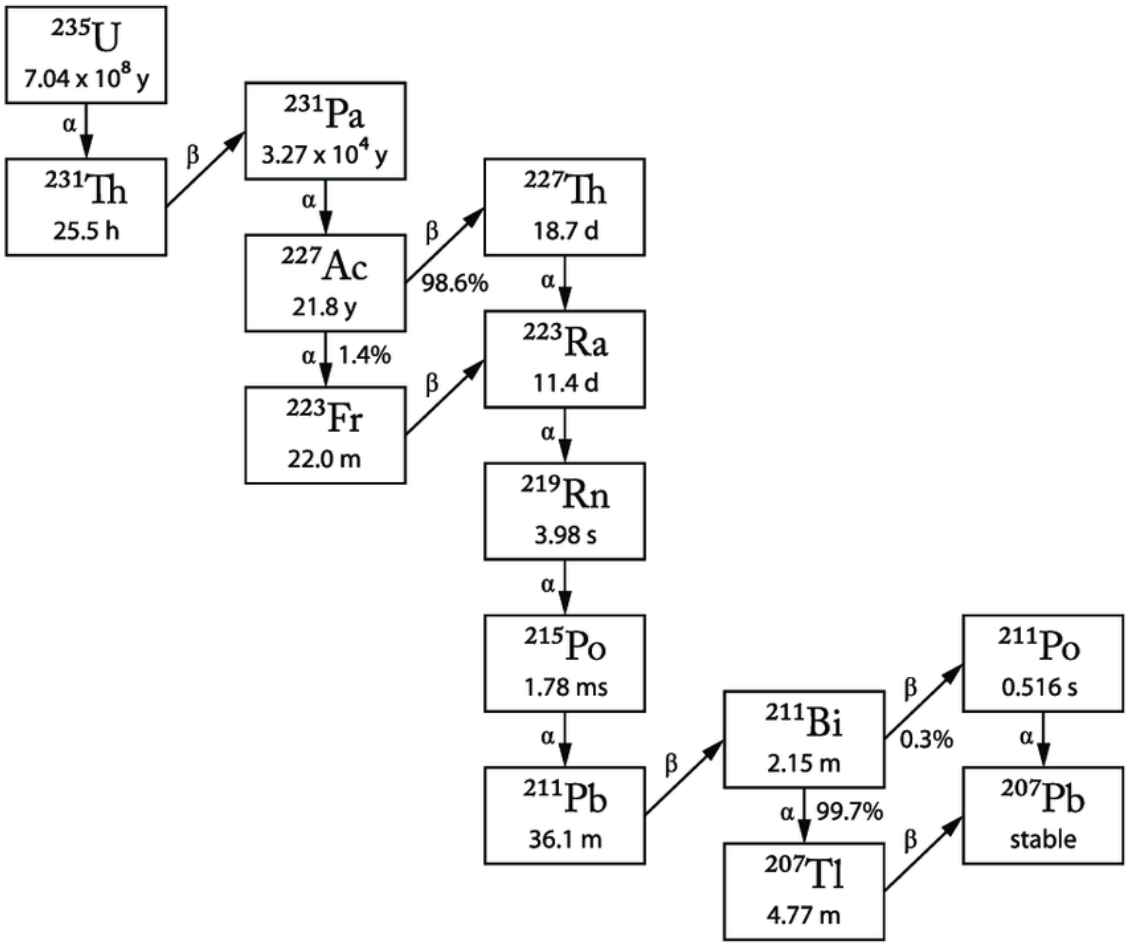

Figure 2.3: Actinium series

Source: Ishimori et al. (2013).

2.7 Effects of Radiation

Ionization is the result of radiation interactions with humans and other organisms (Mavragani et al., 2019; Taj, 2022). This results in morphological and functional alterations that impair cells', organs', and tissues' ability to function normally (Wijerathne et al., 2021). Cells may become altered or perish as a result of the injury (Al-Qadami et al., 2019). Even a significant number of cells can be lost without affecting the majority of the body's organs and tissues (Wijerathne et al., 2021). However, there would be noticeable damage to the organ or tissue as well as to the

person if the number of impacted cells increased (Wijerathne et al., 2021). These consequences, often referred to as deterministic effects, typically result after acute or a single big radiation dosage (Bakar et al., 2019).

2.7.1 Deterministic Effects/ High Doses (Acute) Effect of Radiation

These are the side effects of short-term high radiation exposure times (Bakar et al., 2019). This kind of exposure produces acute or short term effects in the exposed individual or population (Bakar et al., 2019). The consequences appear a few weeks after a significant or acute radiation dosage received in a comparatively short amount of time (Tandon et al., 2022). These consequences result from the significant reduction of cell populations in a number of body organs as a result of cell death and inhibition or postponement of cell division (Bakar et al., 2019). Depending on the amount taken, the primary consequences can be attributed to gastrointestinal, neuromuscular, or bone marrow injury (Tandon et al., 2022).

Nausea and vomiting occur with acute absorbed dosages of 1 Gray (Gy) or more (Carter, 2023). Radiation sickness is the term for this condition, which develops a few hours after exposure due to damage to the intestinal lining's cells (Carter, 2023). Death from absorbed doses above 2 Gy is possible, most likely 10–15 days after exposure (Bakar et al., 2019).

Acute dose-related mortality does not have a clearly defined threshold dose, although there is a very low chance of early death at doses less than 1.5 Gy (Ali et al., 2020). In a similar vein, death is not certain above a certain point (Ali et al., 2020). Nonetheless, the likelihood of surviving an acute dosage of roughly 8 Gy is quite low

(Jin et al., 2021). The dose that, within 60 days of exposure, would be fatal for 50% of the exposed subjects can be reasonably estimated (Jin et al., 2021). Death from secondary infections resulting from the loss of white blood cells, which typically offer protection against infection, is typically the cause of death for doses up to 10 Gy (Van et al., 2020). The zone of infection of death is sometimes referred to as doses ranging from 3 to 10 Gy (Van et al., 2020). Specialized medical therapies can raise survival rates in this range (Shah et al., 2019). A sterile (infection-free) setting might be used to isolate the participants, and bone marrow transfusions could be used to increase the production of white blood cells (Shah et al., 2019).

Radiation doses more than 10 Gy cause a sharp reduction in survival duration, which ranges from 3 to 5 days. This number stays roughly the same until considerably higher doses are attained (Bort et al., 2020). The radiation exposure severely depletes the intestinal lining's cell supply (Carter, 2023). The region of gastrointestinal death, which is caused by a strong bacterial invasion, follows extensive destruction to the intestinal lining (Kulkarni & Guha, 2022). Survival times get much shorter at substantially greater radiation doses (Mohan, 2022). There aren't much human data in this area (Mohan, 2022). Nonetheless, findings from research on animals suggest that the central nervous system is harmed (Mohan, 2022). Additionally, research on animals shows that even in cases where animals are exposed to high doses of radiation (beyond 500 Gy), death does not occur instantly (Friedl et al., 2022).

Skin reddening, or erythema, is another consequence that appears shortly after an acute overexposure to radiation (Lin et al., 2022). The skin is exposed to radiation more often than the majority of other tissues. In particular, this applies to low energy

X-rays and beta radiation. Low energy radiation can cause erythema, or skin reddening, at doses of roughly 3 Gy. Larger exposures can cause pigmentation changes, blistering, and ulceration (Alcocer & Alcocer, 2021).

The radiation exposure levels from the nuclear energy sector and other industrial and medicinal uses are significantly lower than those that could cause side effects to manifest quickly (Holmberg & Pinak, 2021). Only in the extremely rare case of a significant nuclear disaster might such massive dosages be administered (Holmberg & Pinak, 2021). Low dosages obtained during routine procedures, however, can have negative long-term repercussions (Holmberg & Pinak, 2021).

Damage to the eye's lens is another deterministic radiation impact that may not show symptoms for years after exposure (Barnard & Hamada, 2023). In severe circumstances, this impact can result in visible opacities in the human lens, which can lead to visual impairment due to cataracts (McCarron et al., 2022). Once more, there is a threshold dose, necessitating the suggested exposure limit for the human lens (McCarron et al., 2022). Animal research have provided evidence that radiation exposure may marginally shorten an individual's life expectancy (Tong & Hei, 2020; Little, Azizova & Hamada, 2021). The people might not show any particular symptoms brought on by radiation (Tong & Hei, 2020). According to observations made on populations of people exposed to comparatively high radiation levels, life shortening is quite minimal, occurring at a rate of less than one year per sievert (Tong & Hei, 2020).

2.7.2 Stochastic Effects/Low Doses (Chronic) of radiation

These are the long-term or chronic consequences that arise from exposure to low radiation doses over a protracted period of time (Clement et al., 2021). Years after receiving a tiny or chronic dose over a sizable amount of time, there are delayed effects (Clement et al., 2021). No human organ is immediately adversely affected by low doses administered over extended periods of time (Boice et al., 2022). Low radiation doses have impacts at the cellular level, including genetic alterations and the production of cancer, which may take years to manifest. Two categories of effects have been distinguished by (Belli & Tabocchini, 2020; Lowe et al., 2022; Wojcik, 2022).

2.7.3 Genetic/Hereditary Effects of Radiation

Reproductive cell damage is one of the genetic impacts of radiation (Wdowiak et al., 2019). Genetic alterations in particular cells either sperm or egg cells cause this to happen (Meistrich, 2020). The progeny of the radiation-exposed individual inherits the mutations in these reproductive cells (physical mutagenic agent).

Genetic mutations caused by radiation are identical to mutations that occur normally (Grohmann et al., 2019). Without causing any new mutations, radiation accelerates the rate of spontaneous mutation (Lal et al., 2020). Mutations in the reproductive cells may result in major changes in a fertilized egg, which could be one explanation for the lack of genetic consequences of radiation from low dosage exposures observed in human investigations (Reiser et al., 2022). An organism would become nonviable as a result (Wong et al., 2023). During the stages of fertilization, the nonviable organism may spontaneously resorbed or terminate (Colgrove, 2023).

Ionizing radiation can accelerate the rate of mutation, hence its use may also raise the proportion of genetically defective individuals in subsequent generations (Yeager et al., 2021). As a result, those who are exposed may experience significant genetic harm. As a result, stringent measures must be taken to prevent radiation exposure to the general public (Belli & Tabocchini, 2020).

2.7.4 Somatic Effects of Radiation

Somatic effects are cancers suffered by individuals exposed to radiation (Rahman, 2019). From the standpoint of occupational risk, somatic impacts are the most important since the person who is exposed typically a radiation worker suffers the consequences (Santoro et al., 2022). Studies which directly linked cancers to exposure to radiation have been documented. Examples include cancers of the lungs, bones, thyroid, breast, skin leukemia, among others (Jönsson, 2019; Wang et al., 2019; Little et al, 2021).

2.7.5 In-utero Effects of Radiation

The effects of radiation, a physical teratogenic agent, on an embryo or fetus are known as in-utero effects (Iijima, 2021). Developing embryos incur abnormalities as a result of these effects (Tasin et al., 2022). According to Applegate et al. (2021) the effects of radiation exposure during pregnancy can be classified as a subset of the broader category of somatic impacts. Since only the embryo is exposed and not the parents' reproductive cells, the deformity created in the developing embryo or fetus does not suggest a genetic influence (Batra et al., 2022). The true consequences of in-utero exposure that might be observed depend on the stage of fetal development at the time of exposure (Applegate et al., 2021).

2.7.6 Induction of Cancer

Cancer development is a multi-stage, intricate process that takes years to complete (Chen et al., 2019). By causing mutations in the DNA, radiation seems to work well during the start stage of healthy, normal cells. These mutations cause a cell to grow erratically and may cause cancer to develop (Huang & Zhou, 2021).

People who were exposed to relatively high amounts of radiation in the early 20th century, including radiologists and their patients, had a greater incidence of cancer than individuals who were not exposed to radiation (Hauptmann et al., 2023; Lee et al., 2021). Recent comprehensive research on populations exposed to radiation (from radiation therapy, atomic bombs, and occupational exposure) has verified that radiation can cause cancer (Bacinschi, 2018; Lowe et al., 2022).

Researchers in radiobiology have examined the connection between high radiation dosages and cancer. According to these research (Morris et al., 2021; Draeger et al., 2020; Friedl et al., 2022) radiation-induced cancer is mostly caused by damage or changes to genes in the nucleus of the cell. This damage can be brought about directly by the ionizing radiation's interaction with the cell or indirectly by the chemical compounds that radiation interactions within cells produce (Friedl et al., 2022). Most damage can be repaired by cells in a matter of hours, but certain cells might not heal correctly (Lee et al., 2021). It has been discovered that cancer begins with such improperly repaired damage (El Nachef et al., 2022). However, contrary to what El Nachef et al. (2022) suggested, misrepair does not invariably result in cancer. Certain alterations in cells are benign and do not result in cancer (Herrmann, 2020).

Cell susceptibility to radiation-induced cancer can be influenced by a variety of factors, including age, general health, hereditary features, sex, and exposure to other cancer-causing substances like cigarette smoke (Hernando et al., 2021; Tebbi, 2021; Salem, 2023).

2.8 Mechanism of Action of Radiation on Human Body

Ionizing radiations are energetic and penetrating (Guo et al., 2020). Thus, they cause biological effects on human body, irrespective of whether the radiation is natural or man-made (Janiak & Waligórski, 2023), or whether the dose is small or a large (Yeager et al., 2021). They do this by causing ionization of atoms which affect molecules which in turn also affect cells (Kc & Abolfath, 2022). They may also affect tissues which also in turn affect organs and that may also affect the whole body (Farhood et al., 2019).

Radiation damage to cells can result from radiation acting directly or indirectly on the water or DNA molecules inside the cell (Helm & Rudel, 2020). The total amount of DNA damage is caused by both direct and indirect impacts, which differ depending on the kind of cell (Helm & Rudel, 2020).

2.8.1 Direct Action of Radiation on cell DNA

Radiations that target DNA molecules directly or other cellular components essential to a cell's survival are referred to as direct actions (Zaffaroni et al., 2022). The DNA's molecular structure is upset by this contact. Cell damage or perhaps death results from this (Zaffaroni et al., 2022). Remaining damaged cells have the potential to cause cancer or other problems in the future (Zaffaroni et al., 2022). The cell may be

directly destroyed by interfering with its life-sustaining mechanism if enough atoms are impacted to the point where chromosomes are unable to reproduce correctly, or if the information carried by the DNA molecule is significantly altered (Helm & Rudel, 2020).

Overexposure to ionizing radiation can generate a series of complex and prolonged effects in the human body due to ionization or excitation of relatively few molecules (Pazzaglia et al., 2022). According to Moon et al. (2008), the effects of radiation in which zero threshold doses are hypothesized may arise from direct ionization, excitation, and subsequent dissociation of molecules. Information initially encoded in a gene is not passed on to the following generation due to molecular dissociation brought on by ionization or excitation of atoms on DNA molecules (Gao et al., 2021). This could happen in germinal cells, when a point mutation is transferred to the following person (Gao et al., 2021). Additionally, somatic cells may experience it, and daughter cells experience a point mutation as a result (Gao et al., 2021). It's clear that radiation has cumulative biological effects on point mutations, and that even low radiation doses can change the genetic burden, because these changes are transmitted down to the next generation of cells (Moon et al., 2008).

2.8.2 Indirect Action of Radiation on Cell DNA

The human body is composed of about 70–75% water (Lorenzo et al., 2019). Therefore, DNA exposed to radiation has a very small probability of interacting with the radiation due to the small size of DNA molecule (Sakata et al., 2020). Water molecules, which make up the majority of the cell, and other organic molecules within the cell were affected by radiation in the indirect action. (Kyriakou et al.,

2021). Energy absorbed by the water molecules ionizes the molecules to form positive ions (H_2O^+) (Moon et al., 2008) and other highly reactive free radicals [hydroxyl (HO•) and alkoxy (RO_2•)] which are chemically toxic to the cell DNA (Moon et al., 2008).

Unpaired electrons in the structure are a defining feature of free radicals (Başaran et al., 2022). Due to their extreme reactivity, they can interact with DNA molecules and disrupt DNA structure (Başaran et al., 2022). Additionally, harmful to DNA molecules is hydrogen peroxide (H_2O_2) (Başaran et al., 2022). Radiation indirectly affects DNA molecules, which can hinder or even kill a cell (Kyriakou et al., 2021).

The total radiation dosage determines how many free radicals are created by ionizing radiation (Kyriakou et al., 2021). Since more than 70% of a cell is made of water, it has been found that radiation-induced damage to DNA mostly results via an indirect method of action (Saha, 2006).

Hydrogen ion (H^+) and hydroxyl (OH) fragments can be produced when radiation interacts with water molecules, breaking the bonds that hold the molecules together (Etale et al., 2023). Etale et al. (2023) state that these fragments can recombine or mix with other fragments or ions to produce molecules, such as water, that are safe for cells. Additionally, the pieces may mix to generate harmful compounds like hydrogen peroxide (H_2O_2), which could aid in the cell's demise (Etale et al., 2023). Thus, when the human body is irradiated with ionizing radiation, the following chemical reactions occur:

$$H_2O \longrightarrow H_2O^+ + e^- \qquad (4)$$

$H_2O^+ \longrightarrow H^+ + OH$ (5)

The free electron in Equation (1) interacts with neutral water as follows:

$H_2O + e^- \longrightarrow H_2O^-$ (6)

$H_2O^- \longrightarrow H + OH^-$ (7)

Since the bodily fluids already contain considerable amounts of H^+ and OH^- ions, the ions created by Equations 5 and 7 do not provide any risk to the cells (Etale et al., 2023). However, the free radicals ($H^\bullet$ and $OH^\bullet$) may recombine or react with other molecules in human body fluid (Moon et al., 2008). The $OH^\cdot$ free radicals formed may also combine with themselves to produce hydrogen peroxide (H_2O_2) as indicated (Equation 8):

$OH\cdot + OH^- \longrightarrow H_2O_2$ (8)

Apart from the harm resulting from water radiolysis products, other species and reactive nitrogen species can also cause damage to cells (Abot et al., 2022). This might also happen as a result of significant atoms that make up DNA molecules ionizing (Abot et al., 2022).

Direct and indirect effects of radiation on cells cause biological and physiological alterations in the cells (Pignolo et al., 2021). These effects could also manifest seconds or decades after exposure (Pignolo et al., 2021). Takeshima & Ushijima (2019) suggest that the evolution of these modifications may result in genetic and epigenetic changes (Figure 2.4).

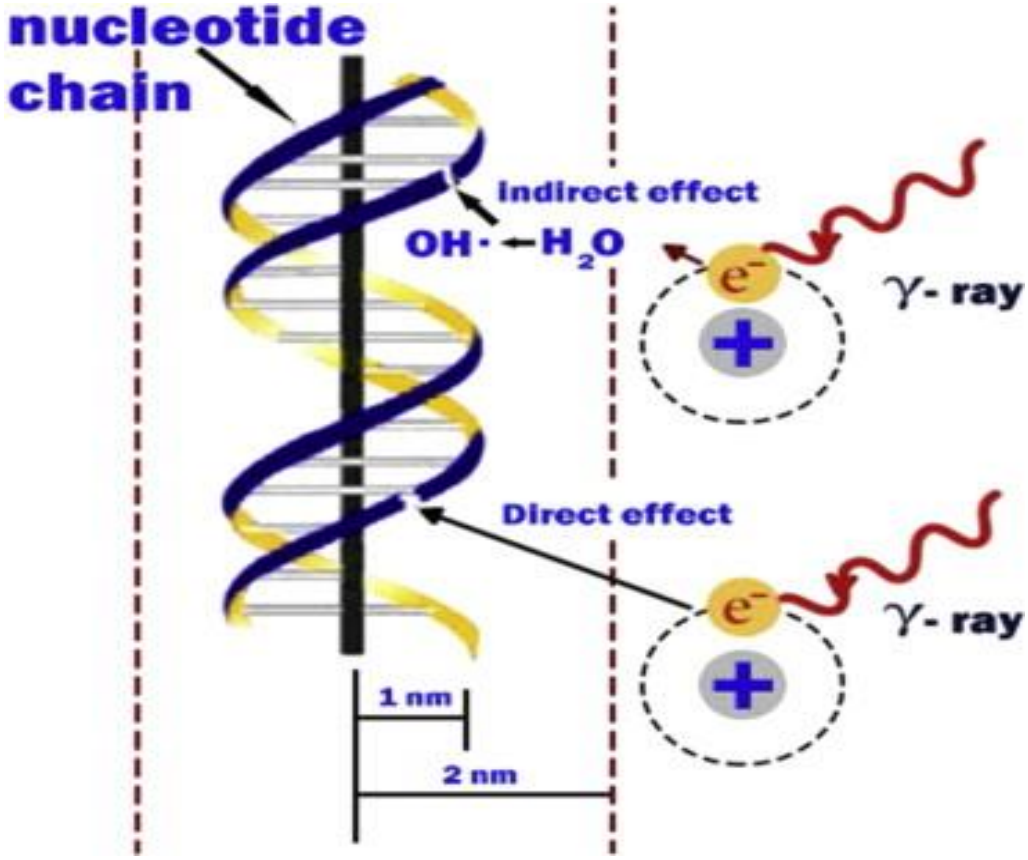

Figure 2.4: Direct and indirect actions of radiation on cell

Source: Desouky et al., (2015)

2.9 Radiological Indicators

2.9.1 External and Internal Hazard Indices

The external hazard index (Hex) and internal hazard index (Hin) were used to calculate human health risk indices.

According to Kovler (2012), the External Hazard Index (Hex) gauges radiation exposure from direct gamma radiation released during radioactive decay. The Internal Hazard Index (Hin) calculates the amount of radiation that is internally exposed to alpha particles as a result of radon-222 (Rn-222) decay and its offspring, which are decay products with short half-lives (Agbalagba & Agbalagba, 2020). The air we

breathe contains radioactive radon and its short-lived decay products, which pose a risk to our respiratory systems. To ensure acceptable levels for people's respiratory organs, the internal hazard index values must be less than or equal to one (1) (Alaboodi et al., 2020). Because a tiny volume of tissue absorbs the great penetrating power of the energy emitted by gamma rays, the risk of internal radiation exposure or injury to the organ is likewise reduced. Consequently, compared to other radiation types (beta and alpha), the internal radiation exposure threat resulting from gamma rays is less severe (Kovler, 2012).

2.9.2 Absorbed Dose of Radionuclides (D)

Absorbed dose is a measure of the amount of energy absorbed by ionizing radiation (UNSCEAR, 2000). It quantifies the radiation energy that might be absorbed by a potentially exposed individual as a result of a specific exposure (UNSCEAR, 2000). Its unit is joules per kilogram (J/kg), with the adopted name of gray (Gy), where 1 Gy = 1 J/kg.

The absorbed dose is not a good indicator of the likely biological effect because the biological effects per unit of absorbed dose varies with the type of radiation and the part of the body exposed (UNSCEAR, 2000). For example, 1 Gy of alpha radiation would be much more biologically damaging than 1 Gy of photon radiation.

For whole body exposure, the quantity effective dose equivalent is used to measure the whole body absorbed dose (UNSCEAR, 2000). Terrestrial gamma-ray radionuclides are responsible for the majority of the absorbed dose rate in the air.

UNSCEAR (2000) provided the airborne absorbed dose rate of natural radionuclides at 1.0 m above ground for external gamma radiation.

2.9.3 Annual Effective Dose Equivalent (AEDE)

The annual effective dose equivalent (AEDE) is used in radiation assessment and protection to quantify the whole body absorbed dose per year (UNSCEAR, 2000). It is measured in milisievert per year (mSv/y).

2.9.4 Excess Lifetime Cancer Risk (ELCR)

The development of cancer is the main long-term health effect on consumers resulting from high radiation exposure. The kind of radionuclides used determines the target organs and forms of cancer. Our yearly radiation exposure from all natural sources is estimated by the International Atomic Energy Agency (IAEA) to be around 2.4 millisieverts (mSv). However, this number might vary by several hundred percent based on one's geographic location (Abass & Muttaleb, 2018).

It takes time for cancer to form as a result of ionizing radiation exposure. If it develops at all, it might take several years (Ugbede & Echeweozo, 2017). Most of the time, cancer doesn't manifest itself until the patient is rather old. Accordingly, the risk that a person may acquire cancer during the course of his lifetime radiation exposure is known as Excess Lifetime Cancer Risk (ELCR) (Agbalagba & Agbalagba, 2020; Ugbede & Echeweozo, 2017).

2.10 Rice Production and Trade

2.10.1 Rice Ecosystems

Three main ecosystems are used to raise rice: irrigated rice systems, lowland rice systems fed by rain, and upland rice systems fed by rain (IRRI, 2013). Irrigated rice systems produce about 75% of the rice produced worldwide (Goswami et al., 2020). Goswami et al. (2020) state that irrigated rice farms are frequently found in humid, sub-humid, subtropical, and humid tropical environments, mostly in Asian countries. Typically, bunded fields with a steady supply of irrigation for one or more crops are used to grow irrigated rice (Dossou-Yovo et al., 2022).

Water levels in rice fields are typically kept between 5 and 10 cm (Yang et al., 2019). Irrigated rice farms are often tiny, with an average size of 0.5 to 2 ha. Irrigated rice is often grown in two or three growing seasons each year as a monoculture (Yang et al., 2019). The average production of an irrigated rice farm is approximately 5.4 t/ha, according to IRRI (2013). High cropping intensity and overuse of agrochemicals, which have the potential to negatively impact human and environmental health, are characteristics of this kind of rice farming system (Wassmann, 2019). Lowland rice that is rain-fed is often grown in bunded fields that are submerged under water during the majority of the cropping season (Singh et al., 2019). 20% of the rice produced worldwide comes from this type of rice cultivation method (Singh et al., 2019). The unpredictability of rainfall in terms of quantity, timing, and duration is a drawback of this rice growing technique (Fadairo et al., 2023). Flooding can take many different forms, from brief, tiny floods to extensive floods that may cover more than 100 cm of water (Fadairo et al., 2023). Rain-fed lowland rice farmers never apply fertilizers because of yield and rain uncertainty; as a result, they do not cultivate improved

varieties (Fadairo et al., 2023). Due to its relatively cheap nature, rain-fed lowland rice cultivation is usually done in parts of the World with high poverty such as Africa, South Asia and parts of Southeast Asia (Koppa & Amarnath, 2021). Because of the aforementioned drawbacks, yields are often quite low, ranging from 1 to 2.5 t/ha (IRRI, 2013).

About 4 % of the total global rice production is from upland rice cultivation (Gadal et al., 2019). Upland rice cultivation is dominant rice cultivation system in Latin America and West Africa (Gadal et al., 2019).

Roughly 40% of the rice-growing regions in Central and West Africa are upland (Gadal et al., 2019). Nearly 70% of rice farmers in Africa are employed by this (IRRI, 2013). Upland rice can be grown in a variety of topographical settings, including valley bottoms and regions with abrupt slopes and undulations (Dananto et al., 2022). Rice farms are usually unrestricted and surface water hardly accumulates during growing season (Gayakwad et al., 2021). As market access to rice remains limited, most upland rice farmers produce other agricultural crops and animals in addition (IRRI, 2013). Upland rice cultivation system is mostly adopted by rice farmers in poverty endemic areas of the world (IRRI, 2013).

2.10.2 Global Rice Production

Production of rice occurs in a variety of habitats, climates, and geographic settings, from the world's rainy regions to its parched deserts (Gadal et al., 2019). Over a hundred countries cultivate rice worldwide (Shekhawat et al., 2020). In comparison to

other cereals, it is the principal crop that is solely consumed by humans (Poutanen et al., 2022).

In 2011, total global rice production was estimated to be around 723 million tonnes (Mohidem et al., 2022). Out of this, about 90 % was from Asia. South America contributed about 6.70 % whilst Africa contributed about 3.30 % (Rahman et al., 2020).

North America was the world's largest producer of rice in 2011, yielding an average of 7.92 t/ha, while Africa produced the least amount, averaging 2.38 t/ha. Africa's production rate fell short of the world average of 4.4 t/ha. Smallholder farmers, who cultivate between 0.5 and 3 hectares, made up the majority of rice farmers in 2011, especially those in Asia and Sub-Saharan Africa (IRRI, 2013).

2.10.3 World Rice Trade

Top seven rice-producing countries are China, India, Indonesia, Bangladesh, Vietnam, Thailand, and Myanmar (Gadal et al., 2019). The main rice exporters and producers are not the same, though, as many nations only grow enough rice for their own needs and have no extra to sell. Gadal et al. (2019) report that the top seven rice exporting nations are as follows: the United States of America (11.5 percent), Vietnam (15.3%), Pakistan (7.2%), China (3.4%), Uruguay (3.1%), and India (10%) are the top seven. Thailand accounts for 38 percent of the total rice export volume. The world's largest rice exporter, Thailand, ships rice to every country in the globe. 10.01 million tons (51.33%) of the nation's total output of milled rice were exported in 2008, bringing in $6 billion (Maitah et al., 2020).

2.10.4 Rice Production in Africa

Africa produced an estimated 26.5 million metric tonnes of rice in 2011, making it the third-largest producer (Tsujimoto et al., 2019). According to Table 4, throughout the years 1990 to 2009, the average annual growth rate of rice production in Africa was practically consistent, ranging from 3.54% to 3.38%) (Senthilkumar et al., 2020). Unfortunately, due to drought and flooding in the majority of African nations, the growth in rice production slowed between 2010 and 2011 (averaging an annual growth rate of 2.53%) (Wopereis, 2013).

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In Africa, not much strides have been made towards rice yields (Mgendi et al., 2019). For approximately a decade (1990 – 1999), yield was 2.15 t/ha (Mgendi et al., 2019). This increased to 2.42 t/ha from 2010 to 2011 (Mgendi et al., 2019). The increased land for rice cultivation accounts for the increased production levels.

In Africa, rice is consumed at the greatest rate (IRRI, 2013). According to IRRI (2013), the average annual rate of rice consumption was 3.3% between 1990 and 1999. But from 2000 to 2009, there was a significant increase, reaching 4.1 percent

(IRRI, 2013). Central Africa experienced the most growth in yearly rice consumption (9%) according to the allocation of this 4.1% on a regional block basis. Africa's other continents were North Africa (1%), West Africa (4%), East Africa (6%), and Southern Africa (3%).

Table 2.4 below shows the production, harvested land size, yield and consumption of rice in Africa from 1990-2011:

Table 2.4: Production, harvested land size, yield and consumption of rice in Africa from 1990-2011

	1990-1999	**2000-2009**	**2010-2011**
Annual average:			
Production (10^6 MT)	14.96510	20.06333	26.20507
Harvested land size (10^6 Ha)	6.94271	8.48528	10.84296
Yield (MT/Ha)	2.15	2.36	2.42
Consumption (10^6 MT)	13.38190	19.51880	
Growth rate per annum (%):			
Production	3.54	3.38	2.53
Harvested land size	2.46	2.66	6.20
Yield	1.06	0.70	-3.25
Consumption	3.27	4.11	

Source: IRRI (2013)

According to IRRI (2013), West Africa is the largest producer of rice in Africa (IRRI, 2013). Out of about 26 million metric tons of rice produced in Africa from 2010 and 2011, West Africa produced about 12 million metric tons. This represents about 46 % of the total rice produced in Africa (IRRI, 2013). The order of rice yields in Africa during 2010 and 2011 were: North Africa (9.39 t/ha) > West Africa (1.99 t/ha) > Central Africa (1.02 t/ha). This shows that West Africa can supply the quantity of rice needed for the continent if it can raise its yield to those of the North Africans (IRRI, 2013).

A trend analysis of rice output before and during the 2007–2008 rice crisis was conducted by Africa Rice Center's Wopereis (2013) (Wopereis, 2013). The US Department of Agriculture provided the data (Wopereis, 2013). According to the findings, the rise in rice yield was responsible for a 71% increase in paddy rice production in Sub-Saharan Africa (Wopereis, 2013). Before the 2007–2008 rice crisis, rice yield accounted for 24% of the rise in rice production (Wopereis, 2013). Additionally, the expansion of land size decrease from 76% prior to the crisis to 29% was credited with contributing to the growth in rice output (Wopereis, 2013).

According to Wopereis's (2013) findings, between 1961 and 2007, the average rice output in Sub-Saharan Africa rose by roughly 11 kg per hectare annually. Nonetheless, between 2007 and 2012, there was a sharp rise of almost 108 kg per hectare annually (Wopereis, 2013). Despite drought and flooding that struck numerous African nations in 2011 and 2012, harvests increased (Wopereis, 2013). This demonstrates how technological innovation, better variety, and smarter management are being used more often (Wopereis, 2013).

2.10.5 Rice Production in Ghana

In Ghana, rice is grown in every agroecological zone and is a staple food (IFPRI, 2020). The yield of paddy rice increased by approximately 10% annually between 2008 and 2019, with a notable 25% growth in 2019 (IFPRI, 2020). Ghana produced 1.23 million tonnes of rice through paddy cultivation in 2021 (IFPRI, 2020). Ghana produced 1.23 million tons of paddy rice in 2021, up from 70,100 tonnes in 1972, growing at an average annual rate of 8.85% (IFPRI, 2020).

In spite of that, over half of the rice consumed is imported, indicating that domestic supply cannot keep up with demand (MoFA 2019). This is indicative of Ghanaian households' increasing fondness for rice, particularly as their population gets wealthier and more urbanized. The significant reliance on imported rice intensifies worries about foreign exchange imbalances and increased susceptibility to global shocks in rice prices. As a result, in addition to giving rice first priority, the 2009 National Rice Development Strategy and the 2017 Planting for Food and Jobs (PFJ) program set high goals for increasing domestic rice output (MOFA, 2017). The goal of the policy is to replace imports of rice with higher-quality rice that can rival imports and be more palatable to Ghanaian customers.

2.10.6 Ghana's Agricultural and Rice Sub-Sector Policy Framework

The Accelerated Agricultural Economic and Development Strategy (AAGDS) was replaced by the Food and Agricultural Sector Development Plan I (FASDEP I), a comprehensive plan that was created in 2002 with an emphasis on assisting the private sector as the main driver of the economy (Asirvatham et al., 2022). According to Asirvatham et al. (2022) FASDEP I was designed to offer a framework for modernizing the agriculture industry and utilizing it as a driver of rural transformation. As stated by Asirvatham et al. (2022) in Ghana's Poverty Reduction Strategy (GPRS I), this was in keeping with the objective set for the private sector.

A poverty and social effect analysis was completed approximately five years after FASDEP I was put into practice (Banson et al., 2016). It was determined that the goal of modernizing impoverished smallholder agriculture was unrealistic due to the incorrect targeting of the poor in an environment with extremely limited access to

markets, credit, technology, and other modernization-promoting factors (Banson et al., 2016). Furthermore, the Ministry of Food and Agriculture's (MoFA) role in encouraging other Ministries, Departments, and Agencies (MDAs) to react to interventions that were outside MoFA's jurisdiction was not made apparent (Banson et al., 2016).

FASDEP II was developed in response to these and other challenges (MOFA-FASDEP II, 2007). According to MOFA-FASDEP II (2007), Ghana's aim for the food and agriculture sector is a modernized agriculture that reduces poverty, creates jobs, and ensures food security while also leading to a structurally altered economy. FASDEP II's goals were created with this idea in mind. Support was intended for five commodities: cowpea, rice, yam, cassava, and maize (MOFA- FASDEP II, 2007). For agricultural development, a value chain approach was chosen (MOFA- FASDEP II, 2007). More emphasis was placed on value addition and market accessibility (MOFA-FASDEP II, 2007; Boateng & Nyaaba, 2014).

Depending on their demands, FASDEP II targets various farmer categories (Boateng & Nyaaba, 2014). An essential component of this method is the use of farmer-based organizations (FBOs) (Asante et al., 2011). Asante et al. (2011) stated that the objective was to support the development of FBOs from the ground up and network them up to the national level through a hierarchy of local, district, and regional groupings. It was anticipated that this would provide them negotiation leverage (MOFA- FASDEP II, 2007). The implementing ministry, MoFA, assists districts in concentrating on no more than two crops (MOFA- FASDEP II, 2007). Crop selection is determined by factors such as comparative advantage, crop relevance to the local

population, and market accessibility (MOFA- FASDEP II, 2007). Supports for the commodities include irrigation, improved planting materials, sustainable land management, and suitable mechanization (MOFA- FASDEP II, 2007). The goal of these supports was to increase output at every stage of the value chain (MOFA-FASDEP II, 2007).

The worldwide food crisis of 2007–2008 prompted the creation of the Ghana National Rice Development Strategy (Lu et al., 2021). The plan aims to quadruple rice production between 2008 and 2018 a ten-year timeframe. In order to achieve self-sufficiency through sustainable rice production, the strategy aims to support national food security, higher income, and decreased poverty (Lu et al., 2021). The amount of rice consumed annually per person rose from 24 kg in 2012–13 to 35 kg in 2016–17 (GSS, 2018). This is predicted to rise to 63 kg by 2018 as a result of urbanization and population expansion (GSS, 2018). Over a ten-year period (2008–2018), the strategy aimed to raise domestic rice production by 10% yearly. This is to support the development of productivity-boosting and gender-sensitive innovations for small-scale local commercial rice producers along the value chain (Lu et al., 2021).

Abukari and Lambongang (2022) stated that the second goal of this strategy is to increase the consumption of rice that is grown locally by means of value addition, quality enhancement, and cross-border marketing. The third goal is to encourage innovative capability among stakeholders for the use of rice byproducts. Building water control systems, managing soil fertility holistically, improving rice varietals, processing rice after harvest, and adding value were among the strategy's main actions (MoFA, 2019).

2.11 Previous Studies on Radioactivity of Rice and Other Foodstuffs

Globally, studies have been conducted on radioactivity of rice and other foodstuffs (Nahar et al., 2018; Yarima et al., 2019; Younis & Tawfiq, 2019). The aims of these studies have been to determine levels of radioactivity in foodstuffs and compare them to the acceptable global average values. Those works also establish baseline data for future reference, determine radiation doses or determine radiological hazard indices associated with consumption of these foodstuffs (Saeed et al., 2011; Awudu et al., 2012; Najam et al., 2015; Abass & Muttaleb, 2018). In order to calculate the radiological risk that comes with eating these foods, scientists have employed a number of metrics, such as the radium equivalent activity, annual gonadal dose equivalent, gamma index, gamma absorbed dose rate, alpha index, ingestion effective dose, and total annual committed effective dose (Ramadhan, et al., 2020; Ugbede & Echeweozo, 2017; Purnama & Damayanti, 2020; Taiwo et al., 2014).

Global reference values used for determination of radiological risk are those recommended by the International Convention for Radiological Protection (Harrison et al., 2021), United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR, 2008) and International Atomic Energy Agency (IAEA, 2019).

Gamma counting techniques with either High Purity Germanium (HPGe) detector or sodium iodide dopped with thalium {NaI (Tl)} detector are commonly used (Hassan et al., 2018; Mauring et al., 2018). Gamma-ray spectrometry is very sensitive, has a non-destructive operational mode and the short test duration and the simplicity of the method give it advantages over other methods (Kovler, 2012).

In 2008, Mlwilo et al. examined the naturally occurring radioactivity levels in maize and rice from several Tanzanian sites. The researchers discovered that the combined yearly committed effective doses for Th-232 and U-238 resulting from the eating of the chosen staple foods for adults, children, and newborns were less than the yearly dose guidelines that are protective of the general public.

The researchers discovered that the average activity concentrations of K-40, Th-232, and U-238 in maize were 48.79 ± 0.11, 4.08 ± 0.01, and 13.23 ± 0.10 Bqkg-1, respectively. K-40, Th-232, and U-238 concentrations in rice were 24.67 ± 0.03, 3.82 ± 0.02, and 5.02 ± 0.02 Bqkg-1, in that order. There was only one sample taken in Zanzibar where cesium-137 (Cs-137) was found. Researchers discovered that foodstuffs (rice) with an activity concentration of 5.57 ± 0.01 Bqkg-1 were imported from Thailand. The researchers concluded that Tanzanian maize production relies heavily on phosphate fertilizers, which accounts for the relatively high average quantities of radionuclides in maize as compared to rice.

The total yearly committed effective doses for babies, children, and adults resulting from the total Th-232 and U-238 intakes of consumption of the staple foods under investigation were, respectively, 0.16, 0.29, and 0.36 mSv/y. These were less than the yearly dose recommendations for public safety.

Aside sampling location, Mlwilo et al. (2008) work did not compare the levels of radionuclides in their samples to acceptable levels of radionuclides for foodstuffs. Their work also did not assess hazard indices as the current work seeks to achieve.

Saeed et al. (2011) conducted a study in Malaysia to ascertain the radioactive contents and radioactivity levels of six distinct rice kinds (Faiza Basmati, white glutinous, black glutinous, Siam, Kurnia, and Utara) that Malaysians ate. The effective dose per annum was found to be below the International Atomic Energy Agency (IAEA) recommended values. The radiation level was measured in the study using the Hyper Pure Germanium Detector (HYPe). Uranium, Thorium, and Potassium had average concentrations of 18.33-25.10) ± 0.01; 35.49-64.97) ± 0.01; and 64.802-109.929) ± 0.001 Bq/kg, in that order.

Effective dose per annum was reported by the researchers to range from 0.02 to 0.03 μSv/year, which were below the recommended dose intake (1 mSv/year) (UNSCEAR, 2006).

This study seeks to measure radionuclide content of rice (both local and imported) consumed in the Tamale metropolis in Ghana. Hyper pure germanium detector will be used in a manner similar to that done by Saeed et al., 2011. This work also seeks to determine external and internal hazard indices as well as excess life time cancer risk as done in similar research works by (Najam et al., 2015), (Nahar et al. 2018), (Abass & Muttaleb, 2018), (Onjefu et al., 2020) and (Yarima et al., 2019).

Foods (cassava, plantain, and millet) eaten by residents of the Accra metropolitan region were found to be radiologically safe to eat, according to Awudu et al. (2012). Using gamma ray spectrometry, Awudu et al. (2012) detected naturally occurring radionuclides (Ra-226, Ra-228, Th-228, and K-40) in several foods consumed by residents of the Accra Metropolitan Area, including cassava, plantain, and millet.

It was discovered that the samples (cassava, plantain, and millet) had high K-40 level (87.77–368.50 Bq/kg). Th-228 (14.93 ± 3.86 Bq/kg) and K-40 (368.50 ± 19.20 Bq/kg) reached their maximum concentrations in cassava. The projected total annual committed effective dosage was 4.64 mSv. Millet supplied the least quantity of radionuclides from food consumption per day, while cassava and plantain contributed the greatest. The public's daily consumption of radionuclides through food (cassava, plantain, and millet) was 411.32 Bq. The daily internal dosage from eating foods containing radionuclides was 0.01 mSv. Using gamma ray spectrometry, Acquah and Aikins (2013) also ascertained the concentration and activity levels of man-made and natural radionuclides in a sample of Ghanaian maize. A High Purity Germanium Detector was utilized to gather, process, and evaluate six distinct types of maize: Mamaba, Abeleehi, Obatanpa, Dodzi, Market Sample A (MS A), and Market Sample B (MS B). Calculations were made for the samples' activity levels and annual effective dosages. Potassium (K-40), Uranium (U-238), Cesium (Cs-134), and Thorium (Th-232) were the most important radionuclides found in the analysis. 0.0039 mSv for dry samples and 0.0012 mSv for washed samples were the average annual effective doses that were obtained.

The study's findings led them to the conclusion that the annual effective doses and radionuclide activity fell below acceptable standard limits. It was concluded that the maize types were fit for human consumption as a result.

In the Volta region of Ghana, Addo et al. (2013) examined naturally occurring radioactive ingestion from cassava that is cultivated and consumed by the local population near a cement mill. In contrast to the findings of numerous other studies

(Awudu et al., 2012; Acquah and Aikins, 2013; Mlwilo et al., 2008, etc.), the yearly dosage limit established for the general public by the International Convention for Radiological Protection (ICRP) is exceeded by the study's annual effective exposure of 1.23 mSv/y. This suggests a risk to human health for the population in the study area that consumes cassava. Ra-226, Th-232, and K-40 were measured by gamma spectrometry in soil and cassava samples that were taken from several farms north, north-east, and east of the Diamond Cement Factory. The activity concentrations of Ra-226 and Th-232 in the soil were similar to the global average, with the exception of K-40, which had a much lower activity concentration. On the other hand, in comparable studies conducted in Nigeria, the amounts in the cassava samples were higher than those found in two high radiation locations. Ra-226 and Th-232 concentration ratios in the assessment of radioactive uptake by cassava exceeded the recommended values set by the International Atomic Energy Agency (IAEA).

A study on gamma-emitting radionuclides (Ra-226, Th-232, and K-40) in rice consumed in Iraq's Nineveh Province was carried out by Najam et al. (2015). The amount of radionuclides in the rice samples was determined by the study using gamma spectrometry fitted with a NaI(Tl) detector. In the range of 51.15 to 109.26 Bq/kg, 13.67 to 71.97 Bq/kg, and 231.87 to 691.71 Bq/kg, respectively, were the radioactive concentrations of Ra-226, Th-232, and K-40. In light of the radionuclides under investigation, the study found that rice in the province was safe to eat radiologically.

The factors utilized to assess the radiological risk of the naturally existing radioactivity included radium equivalent activity, gamma absorbed dose rate, alpha and gamma hazard indices, and internal and external hazard indices.

Abass and Muttaleb (2018) also used gamma ray spectrometer equipped with a NaI(Tl) detector to determine radioactivity concentration of U-238, Th-232 and K-40 in food grains sampled from different markets in the Hilla city (Iraq). Average value of specific activities of U-238 (2.787±0.408 Bq/kg), Th-232 (6.058±0.58 Bq/kg) and K-40 (77.671±38.54) Bq/kg in the samples of rice were within the internationally permissible range.

Average value of Radium Equivalent (17.380 Bq/kg) and Internal Hazard Index (0.051) Bq/kg were also within global limits. Therefore, the study concluded that the investigated rice were radiologically safe for consumption.

In another similar study in Bangladesh, Nahar et al. (2018) evaluated natural radioactivity of Ra-226, Ra-228 and K-40 in rice. They also used gamma-ray spectrometry equipped with High Purity Germanium (HPGe) detector. Hazard linked to each radionuclide was estimated. Average activity levels were Ra-226 (1.09 ± 0.31 Bq/kg), Ra-228 (0.17 ± 0.21 Bq/kg) and K-40 (4.70 ± 1.59 Bq/kg) in the rice samples. Estimated effective doses were Ra-226 (43.69 µSv/y), Ra-228 (16.39 µSv/y) and K-40 (4.15 µSv/y). These values were below UNSCEAR compiled accepted value. The calculated excess lifetime cancer risk (ELCR) values via rice consumption were Ra-226 ($4.63 \times 10^{-5} - 1.38 \times 10^{-4}$), Ra-228 ($1.06 \times 10^{-5} - 9.97 \times 10^{-5}$) and K-40 (6.57 ×

10^{-6} − 3.72 × 10^{-5}). These values were below acceptable limit of 0.29×10^{-3} for radiological risk (Patra et al., 2013).

Van et al. (2019) employed α-, γ-spectrometry and liquid scintillation counting techniques to assess radioactivity concentrations of Th-232 and U-238 decay chains, K-40, Sr-90, Cs-137, and Pu-(239+240) in raw and cooked food of population in Red River delta region (Vietnam). K-40 (347 ± 55) Bq/kg dw) was found in cooked food at a concentration higher than that of the other radionuclides (23 ± 5) in rice and (347 ± 50) Bq/kg dw) in tofu. Po-210 content in cooked food ranged from (4.0 ± 1.6) Bqkg−1dw (in rice) to its limit of detection (LOD) of 5 x 10-3. Th-232 and U-238 chain concentrations in the meal ranged from (1.1 ± 0.3) Bq/kg dw to a low LOD of 0.02. In the study region, the average annual committed effective dose to adults was 0.32 mSv/a, with a range of 0.24 to 0.42 mSv/a. Tofu, rice, and leafy vegetables each made up 16.2%, 24.4%, and 21.3% of the total. Adults who regularly consume diets with committed effective dosages fell within the global range established by other nations. The results indicated that, in terms of radiation exposure, Vietnamese foods are safe for human consumption.

Onjefu et al. (2020) have carried out a study on the assessment of naturally occurring radionuclides in a few selected varieties of regularly consumed rice in Namibia. A high-purity germanium detector-equipped gamma spectrometer was also employed by the researchers. In the evaluated rice samples, the average activity concentrations were U-238 (0.39 ± 0.04 Bq/kg), Th-232 (0.28 ± 0.06 Bq/kg), and K-40 (13.00 ± 058 Bq/kg). These numbers were used to compute the excess life cancer risk, gamma index, annual committed effective dosage, daily radioactivity intake, and total dose

intake. These radiological parameters were below the global average values, even if they compared favourably with those analyzed in previous research. The study also found that there was no radiological risk associated with the examined rice that was marketed in Namibia due to the presence of Th-232, K-40, and U-238.

In Nigeria, natural radioactivity in maize was evaluated by Yarima et al. (2019). HPGe, a gamma-ray spectrometer, was also used by the researchers. In the samples of maize, the mean activity concentrations were Ra-226 (8.6 ± 0.7 Bq/kg), Th-232 (2.8 ± 0.5 Bq/kg), and K-40 (315 ± 18 Bq/kg). For Ra-226 and Th-232, the activity concentrations that were measured fell short of the global average values, which are 67 Bq/kg and 82 Bq/kg, respectively. K-40 activity concentration was higher than the average value of 310 Bq/kg worldwide.

The annual effective dosage derived from maize eating did not surpass the recommended ingestion dose limit of 290 μSv/y by UNSCEAR. Based on a 1 mSv annual exposure limit for the general public, the predicted lifetime cancer risk was less than the ICRP (1991) cancer risk factor of 2.5 × 10−3 (Yarima et al., 2019). Therefore, the study also found that consuming maize and other items derived from it did not pose any health concerns to the Nigerian population.

U-238, Th-232, and K-40 activity concentrations were detected by Younis and Tawfiq (2019) in a sample of amber rice grown in southern Baghdad, Iraq. Gamma-ray spectrometer equipped with NaI (Tl) detector was used. Average specific activities for the investigated radionuclides were below the acceptable global average values of ICRP. Annual effective dose estimated for adults was below 1 mSv/y permissible

limit recommended by ICRP (Paquet et al., 2019). Th-232 (B.D.L to 3.37) Bq/kg, K-40 (4.48 to 35.7) Bq/kg, and U-238 (2.68 to 10.81) Bq/kg were the range of activity concentrations. The rice's annual effective doses for adult consumers were as follows: Th-232 (B.D.L. to 0.42) x10-5 Sv/y; K-40 (0.17 to 1.2) x10-5 Sv/y; and U-238 (0.41 to 1.6) x 10-5 Sv/y. Machraoui et al. (2019) ascertained the activity concentrations of man-made and natural radionuclides in several vegetable samples, including leafy, root, and fruit vegetables, as well as animal-derived consumables including milk, meat (chicken and beef), fish, and eggs. Four cities in Southern Tunisia, home to extensive phosphate production businesses, were chosen for the study's various locations.

The goal of the study was to establish a baseline database on radionuclide concentrations in food products so that the public's exposure to radiation from routinely ingesting the food under inquiry could be evaluated. K-40, Pb-210, Ra-226, Ra-228, and Cs-137 activity concentrations were measured using gamma spectrometry fitted with an HPGe detector. The observed activity concentrations and the ICRP-provided dosage factors were used to estimate the doses. Additionally, the dosage from radioactive ingestion indirectly through mineral water was calculated. The age groups receiving the total yearly effective doses were those of 1 year (2.2 mSv/y), 5–15 year (1.4 mSv/y), and (>17 year) (0.7 mSv/y). Po-210 and Pb-210 were the radionuclides that contributed the most to the overall dosage among those that were evaluated.

A study by Ugbede (2022) also assessed levels of natural radioactivity (K-40, Th-232 and U-238) and their committed effective doses in freshly harvested rice grains. The

study was done in three different paddy fields (F1, F2, and F3) in Ebonyi State, Nigeria. The researchers used gamma spectrometer equipped with NaI(TI) detector. Average activity concentrations in the sampled rice grains were K-40(129.0 ± 13.0) Bq/kg, Th-232(3.0 ± 1.3) Bq/kg and U-238 (11.7 ± 4.3) Bq/kg (farm F1); K-40 (129.1 ± 18.5) Bq/kg, Th-232 (4.3 ± 1.6) Bq/kg and U-238 (8.5 ± 4.2) Bq/kg (farm F2); and K-40 (89.2 ± 10.3) Bq/kg, Th-232 (4.5 ± 2.1) Bq/kg and U-238 (2.7 ± 1.0) Bq/kg (farm F3). Total radioactivity content of the rice was attributed to K-40, which contributed about 90% (farm F1), 91% (farms F2) and 91% (farm F3).

The F1 (0.12 mSv/year), F2 (0.11 mSv/year), and F3 (0.06 mSv/year) committed effective doses were estimated. The acceptable level for radiological risk was met by the committed effective doses and the cancer risks associated with the quantities of K-40, Th-232, and U-238.

According to the study, there was little chance of radioactive health risks for the general public while consuming the items under review. Rice and salt samples that were sold in Baghdad's local markets were found to contain particular activity of naturally occurring radioactive elements, as reported by Hameed, Rejah, and Muter (2016). While the H_{in} and H_{ex} in the rice samples were below unity, that in a salt sample was found to be more than one (1). That salt brand was considered radiologically unsafe and therefore ban on it's importation was recommended.

The literature reviewed shows that natural and anthropogenic radionuclides have been found in some foods including rice. Although most of foodstuffs investigated have been found to be radiologically safe for consumption, the contents of radionuclides in

some of them were above global averages. This indicates that these foods were unsafe for consumption.

CHAPTER THREE

METHODOLOGY

An overview of the study region, sampling, and sample preparation techniques are provided in this chapter. It also includes information on gamma ray spectrometry, how natural radionuclide concentrations in the samples were determined, how radiological parameters (like the absorbed dose rate, annual effective dose equivalent, excess lifetime cancer risk, and internal and external hazard indices) were determined, and how the data from this work were presented statistically.

3.1 Description of the Study Area

The study was conducted in the Metropolis of Tamale in the Northern Region of Ghana. There are 261 Metropolitan, Municipal, and District Assemblies (MMDAs) in Ghana, including this metropolis. It belongs to the Northern Region's 16 MMDAs as well. The total land area of the metropolis is 750 km^2 (GSS, 2021). According to the GSS (2021), this amounts to roughly 13% of the Northern Region's entire land area. There are 374,744 people living in the metropolis (GSS, 2021). This number is made up of 189,693 females and 185,051 males, or roughly 51% and 49%, respectively (GSS, 2021).

According to GSS (2010), Tamale serves as both the regional and the metropolitan capital of the Northern Region. It is located between latitudes 9° 16 and 9° 34 North and longitudes 0° 36 and 0° 57 West (GSS, 2010).

Due to the presence of financial institutions and non-governmental organizations (NGOs), among other things, Tamale, the third-largest city in Ghana, is thought to be the fastest developing city in West Africa (Gyasi et al., 2014; Abukari, Donkoh & Ehiakpo, 2019).

One of the six metropolitan assemblies in the nation is Tamale. Furthermore, according to GSS (2010), it is the sole metropolis in the five regions of Northern Ghana: Upper East, Upper West, North-East, Savannah, and Northern regions.

As per GSS (2010), the metropolis is bordered to the east by the Mion district and to the north by Savelugu municipality. Along with Central Gonja District to the south-west, Gonja District to the east, and Sagnerigu Municipal to the north-west are its neighbours (GSS, 2010).

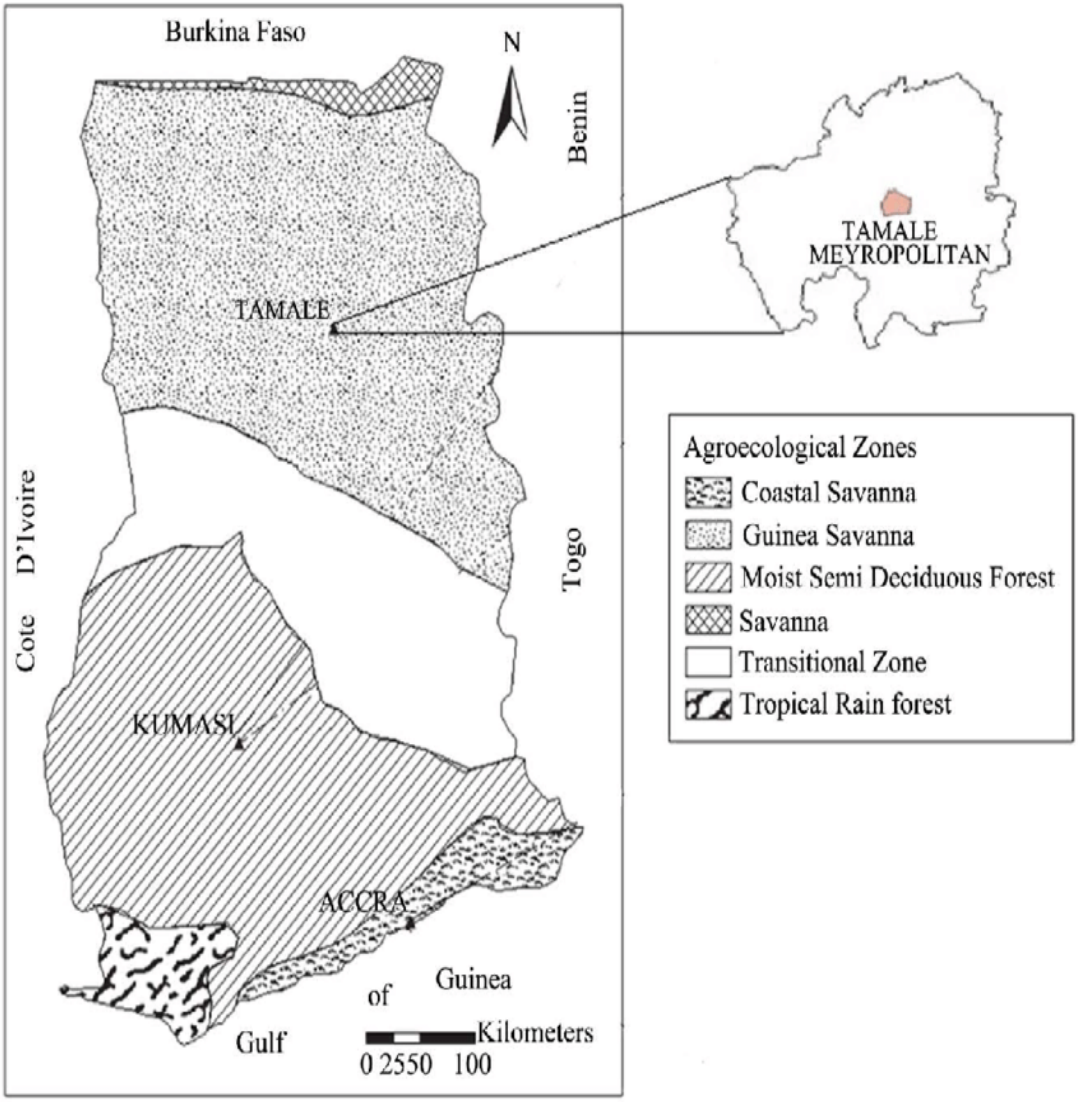

Figure 3.1: Map of Ghana showing the Tamale metropolis of the northern region, adopted from Abagale (2021).

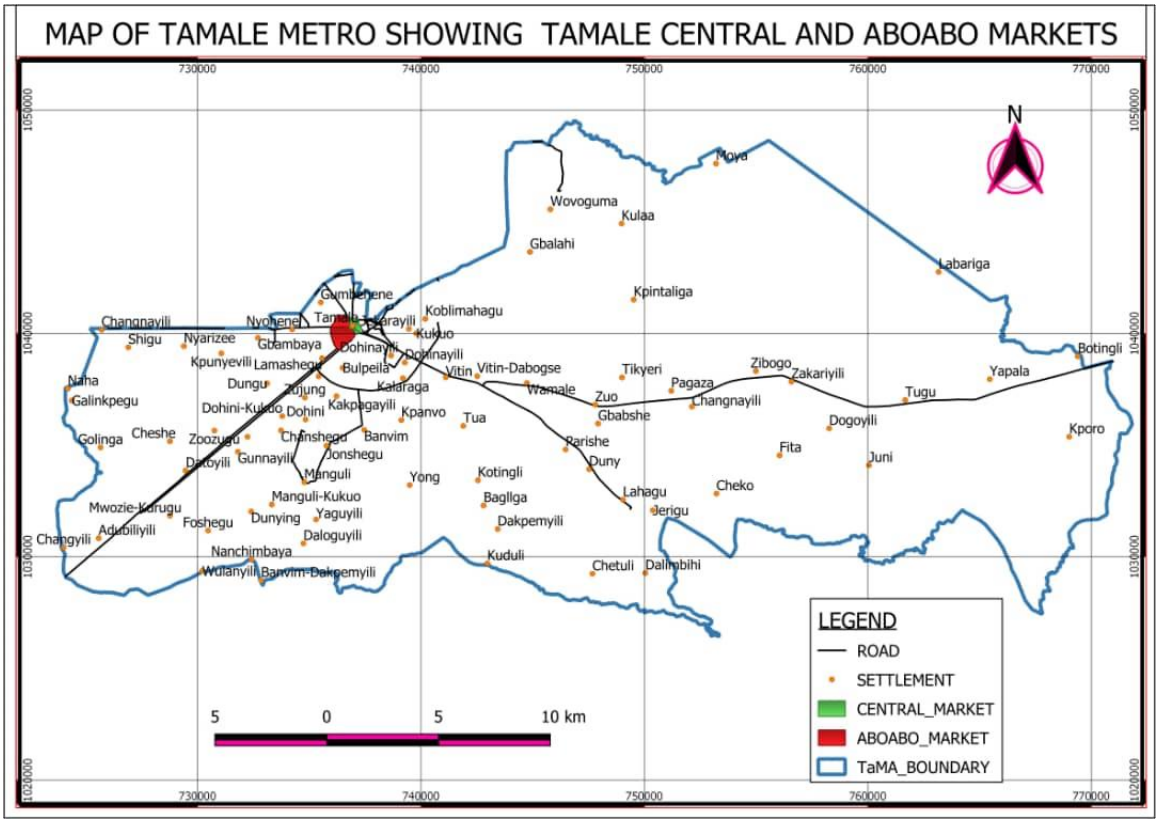

Figure 3.2: Map showing sampled markets in the study area

Source: TaMA (2022)

Within the Metropolis, there are five operational markets: Tamale Central, Aboabo, Lamashegu, Kakpagyili, and Kukuo. Further satellite markets can be found in various parts of the metropolis (GSS, 2010). Because they are the biggest and the primary food markets for other markets in the metropolis, Tamale Central and Aboabo markets were chosen for this study.

Tamale's advantageous position means that there is a market for regional agricultural products in the Metropolis. It also provides commercial services to the southern regions of Ghana and other nearby districts. Due to its location, the Metropolis stands to benefit economically from commerce with Burkina Faso, Niger, Mali, and Togo, among other neighboring West African nations (GSS, 2010).

3.2 Sampling and Sample Preparation

Eight rice samples (local and imported) were bought from the two major markets (Tamale central and Aboabo markets) in the metropolis in May 2022. Simple random sampling techniques were employed in sampling. Two locally produced and two imported rice samples were purchased from each of the two markets. To ensure homogeneity, each pre-weighed sample was dried in a n oven and then ground into a powder. For at least four weeks, the homogenized samples were kept in sealed plastic containers to allow the parent and daughter radionuclides to achieve secular equilibrium.

Plate 3.1: A photo showing buying of samples in the market

Plate 3.2: A photo showing sample preparation in the laboratory

3.3 Gamma Ray Spectrometry

Gamma ray spectrometric analysis was done at the Radiation Protection Institute Gamma Laboratory of the Ghana Atomic Energy Commission (GAEC). A high purity germanium (HPGe) p-type detector with 46 mm in length and 61 mm in active diameter was used to analyze the rice samples. The detector was set under the following conditions: relative efficiency: 25%; energy resolution: 2.0 keV; and Full Width at Half Maximum (FWHM), 1.332 MeV. The detector was coupled with Co-60 emission and 16 k Multichannel Analyzers for data acquisition. Genie 2000 software from Canberra was used to analyze the spectra. To reduce the interference of

background radiation from terrestrial and extraterrestrial sources in the measured spectrum, the detector was enclosed in a 100 mm passive shielding made of lead, copper, cadmium, and plexiglass (3mm each). Liquid nitrogen at a temperature of -196°C (77 K) was used to cool the detector. For efficiency calibration, standard radionuclides in solid water with a volume of 1000 cm^3 and density of 0.98 gcm^{-3} were used.

3.3.1 Calibration of the Gamma Spectroscopy System

To obtain both the qualitative and quantitative results from the rice samples, both energy and efficiency calibration was performed for the HpGe detector in the laboratory before counting and analysis was done on the detector.

3.3.2 Energy Calibration

The energy calibration of an HpGe detector system which establishes a relationship between the electronic signals produced by the detector and the corresponding gamma ray energies being detected is one of the essential requirements in nuclear spectroscopy measurements (Harb, 2008). This was achieved by comparing both the spectrum of a standard source releasing known energies and the measured energy peak positions. The standard used was the ENEAMRL-1665 multigamma soil standard source in a 500ml Marinelli beaker with 1.38 $kgdm^{-3}$ density. The Ente per le Nuove Tecnologie, l'Energia e l'Ambiente in Rome provided the ENEAMRL-1665 multigamma standard source for this study. This source is a mixture of eight radionuclides that produce gamma rays within the energy range of 60keV to 2MeV, including K-40, Cd-109, Ce-139, Co-57, Co-60, Cs-137, Sn-113, and Y-88. The standard was counted for 36000 seconds to generate a spectrum. The calibration

process involved locating the centroid for each peak and assigning known energies to each channel number, resulting in a linear relationship between the channel number and energy. The detector's ability to distinguish between closely lying peaks was estimated to be 2.0 keV at the 1332 keV gamma ray energy of Co-60, with a relative efficiency of 25%.

3.3.3 Efficiency Calibration

The ratio of actual events that the detector registers to all the events that the radiation source emits is the efficiency of the detector. A precise efficiency calibration of the detector system is required to quantify radionuclides in a sample. Prior to determining the efficiency, the detector system must be fully set up and adjusted and this should be maintained until a new calibration is carried out (IAEA, 1989).

To determine the efficiency, a standard is counted on the detector for 10 hours. The efficiencies were calculated using the net counts for each of the full energy events in the spectrum and their corresponding energies. The efficiencies were calculated using the following Equation (9) (Darko & Faanu, 2007).

Efficiency of the detector = $Ns/(P \times m \times T \times A)$ …… (9);

where P= gamma ray emission probability of the standard; T= counting time (10hrs=36000s); Ns =Net area = Total photo peak count- the Background count; A= Activity concentration of the standard.

3.3.4 Background Radiation

To minimize statistical counting error, natural radioactive nuclei in the samples were counted using a gamma detector for a duration of 36000 seconds. To evaluate

background radiation, an empty 1L Marinelli beaker was counted for 36000 seconds with the same geometry as the samples. The background radiation spectra were used to correct the net peak area of the measured isotopes' gamma energies and to calculate the Minimum Detectable Activities.

Determination of the elements was done using photo peak comparison with standard samples. The activity concentrations of Th-232 and K-40 were obtained directly from the peak photon energies of 2.62 MeV and 1.46 MeV respectively. The activity concentrations of Ra-226, Ra-228 and Th-228 were determined indirectly from the peaks of Bi-214 (609.3 keV), Ac-228 (911 keV) and Tl-208 (2614 keV), respectively.

3.3.5 Minimum Detectable Activity

The Minimum Detectable Activity (MDA) is the smallest quantity that we can detect with a system, in specific measurement conditions (Done & Ioan, 2016). The Romanian National Commission of Nuclear Activities Control (CNCAN) also defined MDA as the smallest activity of a radionuclide which can be detected in a sample, with a predefined probability of 95%, taking into account of 5% probability of making type I errors (assumption that a radionuclide is present, but actually it is not) and making type II errors: assumption that the radionuclide is not present, but actually it is (Done & Ioan, 2016).

The relationship between the Minimum Detectable Activity, gamma yield and the absolute efficiency expressed in equation (10):

Minimum Detectable Activity= $(1.645\sqrt{B})/(\varepsilon \times P \times T \times M)$ ……... (10);

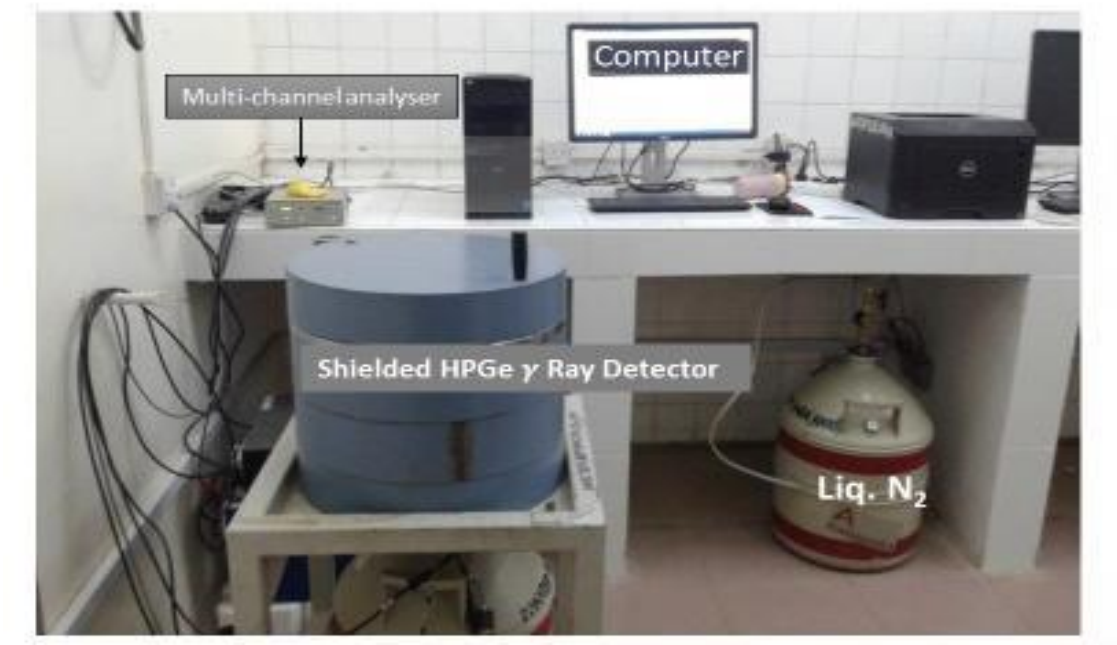

Plate 3.3: A photo showing gamma ray spectrometer (Source: Radiation Protection Institute Gamma Lab-GAEC gallery, 2022)

3.4 Calculation of the Concentrations of the Natural Radionuclides

The activity concentration of the natural radionuclides in each sample was calculated using Equation 11 (Amatullah et al., 2023):

$$A = \frac{N}{\varepsilon P_\gamma t m} \qquad (11)$$

Where,

A=activity concentration in $Bqkg^{-1}$

N=net counts of the corresponding photopeak

Ɛ=detector efficiency evaluated in function of the transition energy

P_γ = the emission probability per disintegration

t= sample counting time in seconds

m= mass of the sample in kg.

3.5 Statistical Analysis of Data Obtained from Natural Radionuclide Concentrations

Data from naturally occurring radionuclide concentrations were analyzed using the t-test and descriptive statistics (mean, standard deviation). To ascertain whether there are any appreciable variations in the natural radioactive contents of the imported and local rice, the means of the radionuclides in each were calculated and compared using paired t-test.

Minitab software (version 16) was used to determine existence of significant difference between concentrations of natural radionuclides from the local and imported rice varieties or otherwise. The samples (local and imported rice) used were compared by matching values computed for corresponding natural radionuclide.

The null hypothesis, H_0 (no significance difference between radionuclide concentrations of local and imported rice varieties. Decisions on the hypothesis were based on p-value obtained after the test. The null hypothesis was maintained when the p-value was higher than a predetermined threshold value of 0.05.

To further assess the radiological risks connected to the rice, the following metrics were used: excess lifetime cancer risk (ELCR), annual effective dose equivalent (AEDE), internal hazard index (Hin), and external hazard index (Hex).

3.6 Calculations of External and Internal Hazard Indices

The formula employed by Taiwo et al. (2014) to determine the external hazard index, or Hex, is: $Ex = (A_{Ra}/370) + (A_{Th}/259) + (A_K/4810)$, where A_{Ra}, A_{Th}, and A_K stand for

activity concentrations of Ra-226, Th-232 and K-40, respectively. In order to qualify as insignificant for radiation risk, the external hazard index values need to be less than or equal to one (1) (Alaboodi et al., 2020).

Equation 12 was utilized to determine the internal hazard index (Hin) (Taiwo et al., 2014).

$$Hin = (A_{Th}/259) + (A_K/4810) + (A_{Ra}/185) \quad (12)$$

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

3.7 Calculations of Absorbed Dose of Radionuclides (D)

D was calculated from Equation 13:

$$D = 0.0417C_K + 0.604C_{Th} + 0.462C_{Ra} \quad (13)$$

where,

D= the absorbed dose rate which is measured in (nGy/hr)

C_K = the activity concentration of K-40 in Bq/kg

C_{Th} = the activity concentration of Th-232 in Bq/kg

C_{Ra} = the activity concentration of Ra-226 in Bq/kg

The absorbed dose rate in air was used to calculate the outdoor annual effective dose equivalent for individuals.

3.8 Calculations of Annual Effective Dose Equivalent (AEDE)

The annual effective dose equivalent was calculated using Equation (14) (UNSCEAR, 2000):

$$AEDE_{outdoor} = D \times 8760 \times 0.7 \times 0.2 \times 10^{-6} \quad (14)$$

where,

$AEDE_{outdoor}$ = Annual outdoor Effective Dose Equivalent (AEDE) measured in $mSvy^{-1}$

D= the absorbed dose rate which is measured in nGy/hr

0.2 = outdoor occupancy factor, assuming that a man spends 20% of their time outdoors (Adekoya et al., 2022), measured in yr^{-1}.

0.7 = the dose conversion factor measured in Sv/Gy

8760= time spent exposed to gamma rays in a year, measured in hours.

3.9 Calculations of Excess Lifetime Cancer Risk (ELCR)

Excess Lifetime Cancer Risk was calculated using Equation 15:

$$ELCR = AEDE \times DL \times RF \qquad (15)$$

Where,

$ELCR_{outdoor}$ = Outdoor Excess lifetime Cancer Risk

$AEDE_{outdoor}$ = Outdoor Annual Effective Dose equivalent

DL=Duration of life/average life expectancy (70 years)

RF=Risk factor (S/v), i.e., fatal cancer risk per Sievert. ICRP uses a RF of 0.05 for the public for stochastic effects (Taskin, 2009).

The worldwide recommended value of $ELCR_{outdoor}$ is 0.29×10^{-3} (Ugbede & Echeweozo, 2017; Penabei et al., 2018).

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter presents and discusses the results obtained (concentrations of the natural radionuclides) in the rice samples (local and imported). The chapter further discusses the effects of the radionuclides on consumers of the rice based on the mean concentrations of radionuclides present in the rice samples. For every natural radionuclide that has been detected, it also covers the excess life cancer risk, absorbed dose rate, annual effective dosage equivalent, and internal and external hazard indices.

4.1 Concentrations of the Natural Radionuclides in Local Rice Samples

Mean activity concentrations of natural radionuclides in the local rice in the Tamale metropolis were calculated and the data presented (Figure 4.1).

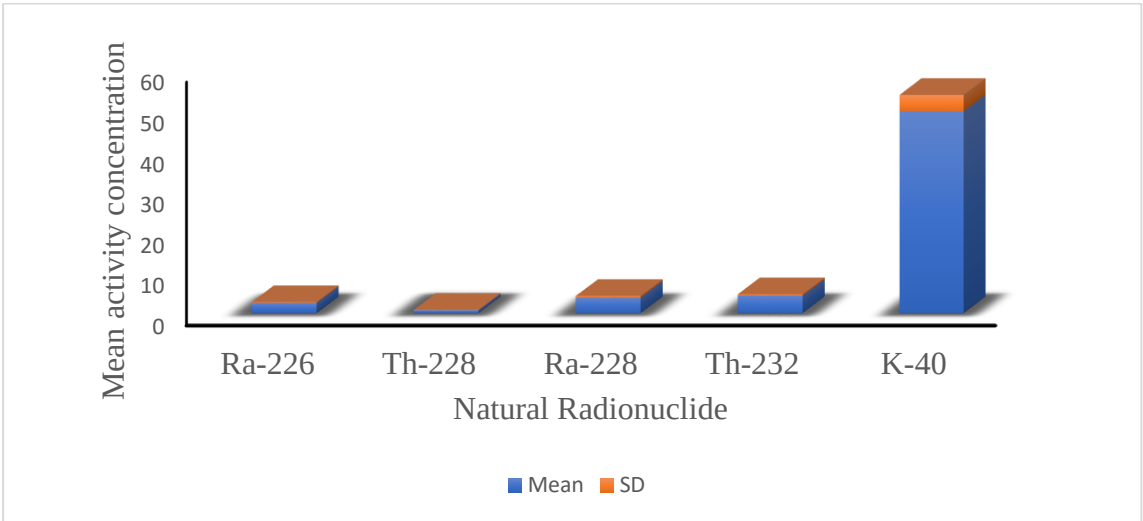

Figure 4.1: A plot of mean activity concentrations (Bq/kg) of natural radionuclides in local rice in Tamale metropolis

Ra-226, Th-232, and K-40 were found in all four samples of the local rice, whereas Th-228 and Ra-228 were found in three of the four samples, according to the mean activity concentrations shown in Figure 4.1.

Whereas Th-228's activity concentration ranged from (BDL to 1.2 ± 0.10) Bq/kg with an average of (0.7 ± 0.08) Bq/kg, Ra-226's activity concentration ranged from (0.4 ± 0.03 to 5.4 ± 0.43) Bq/kg with an average of (2.5 ± 0.19) Bq/kg. Th-232's activity concentration varied from (0.3 ± 0.02 to 10.4 ± 0.83) Bq/kg with an average of (4.28 ± 0.34) Bq/kg, while Ra-228's ranged from (BDL to 10.5 ± 0.84) Bq/kg with an average of (3.8 ± 0.40) Bq/kg. K-40 had an average of (49.73 ± 3.99) Bq/kg and ranged from (49.6 ± 4.01 to 60 ± 4.8) Bq/kg.

K-40 had the highest mean value while Th-228 had the lowest mean value. The relatively high values of K-40 can partly be attributed to the use of fertilizer in rice production, since most fertilizers have high potassium content as reported by (Mohammed et al., 2021). It could also be partly due to natural abundance of potassium in plants since it is required for a variety of plant functions (Sardans & Peñuelas, 2021).

The relatively low activity concentration of Th-228 may be due to the fact that it is a trace isotope of thorium and has a shorter half-life of 1.92 years compared to that of Th-232 (14.05 billion years).

Radium-228 mean activity concentration (3.8 ± 0.40) Bq/kg was higher than that of Ra-226 (2.5 ± 0.19) Bq/kg. Ra-226 is a radioactive decay product in the U-238 decay

series, whereas Ra-228 is a radioactive decay product in the Th-232 decay series. On average, there are three times as many Th-232 in the Earth's crust than U-238 (Al-Full & Khattab, 2022). Therefore, the greater abundance of Th-232 than U-238 could account for the higher concentration of Ra-228 than Ra-226.

Mean activity concentration of Th-232 (4.28 ± 0.34) Bq/kg is above that of Th-228 (0.7 ± 0.08) Bq/kg as shown in Figure 4.1. This could be due to the fact that Th-232 is the most stable isotope of thorium (Supriadi et al., 2020). It's half-life is 14.05 billion years and so it decays very slowly (Supriadi et al., 2020). The natural quantity of thorium in the earth is nearly constant because of this slow rate of disintegration (US EPA, 2014).

The natural radionuclides that were detected had mean activity concentrations that were by far lower than the global standard values set by UNSCEAR (2000) as shown in Figure 4.2 below:

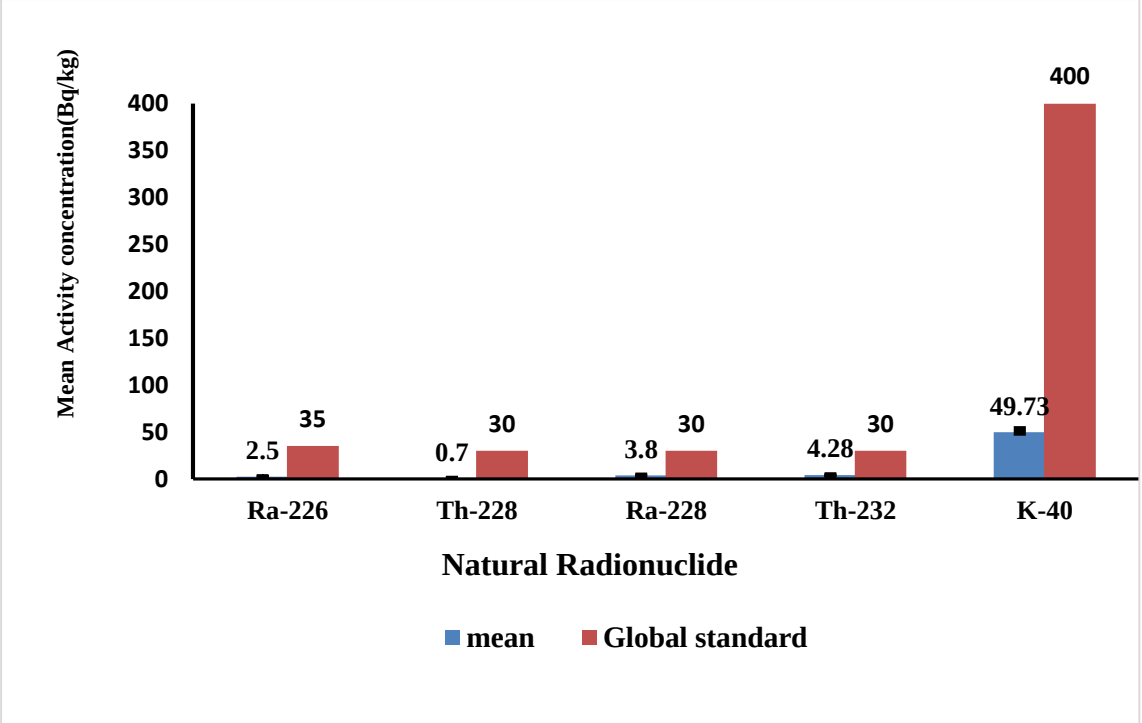

Figure 4.2: A plot of mean activity concentrations (Bq/kg) of natural radionuclides in local rice in Tamale metropolis compared with the global standard values

The mean activity concentration of Ra-226 was found to be (2.5 ± 0.19 Bq/kg), indicating a lower value than the global standard of 35 Bq/kg as per UNSCEAR (2000). Th-232 had an average activity concentration of (4.28±0.34) Bq/kg. This is below the UNSCEAR (2000) world mean value of 30 Bq/kg. The global average activity concentration of 400 Bq/kg (UNSCEAR 2000) for K-40 is greater than its average activity concentration of 49.73±3.99) Bq/kg.

The lower mean values of radionuclides in the local rice compared to UNSCEAR (2000) global standards suggest the radioactivity levels in the rice are within permissible limits. This means the local rice are safe and can be exported into

international markets for sale. The results of this investigation align with numerous previous studies conducted worldwide (Younis and Tawfiq, 2019; Abass and Muttaleb, 2018).

The lack of radioactively linked minerals including zircon, monazite, iron oxides, and fluorite in the soil where the rice was grown may be the cause of the low amounts of natural radionuclides discovered in the rice samples under study.

Table 4.1 shows a comparison of the investigated natural radionuclides in this study with similar works.

Table 4.1: Activity concentrations (Bq/kg) of Ra-226, Th-232 and K-40 in rice samples investigated in this study compared with similar works across the world.

Origin	Ra-226	Th-232	K-40	Reference
Ghana	2.5	4.28	49.73	present study
Malaysia	-	35-65	65-110	Saeed et al. (2011)
Tanzania	-	3.82	24.67	Mlwilo et al. (2007)
Iraq	51.15-109.26	13.67-71.97	231.87-691.71	Najam et al. (2015)
Bangladesh	1.09	-	4.70	Nahar et al. (2018)
Namibia	-	0.28	13.00	Onjefu et al. (2019)

Concentrations of the natural radionuclides Ra-226 (2.5 Bq/kg), Th-232(4.28 Bq/kg) and K-40 (49.73 Bq/kg) recorded in this study were below those reported by Saeed et al (2011) in Malaysia and by Najam et al. (2015), Abass & Muttaleb (2018) in Iraq. However, the values of the current study are higher than those reported by Mlwilo et al. (2011) in Tanzania and Nahar et al. (2018) in Bangladesh.

Differences in the chemical composition of the soil, its geological structure, and agricultural practices, such as the type of fertilizer and insecticides used, could be the

reason for the observed differences in the activity concentrations of the natural radionuclides under study compared to those found in the reference works (Siraz et al., 2023).

4.2 Concentrations of Natural Radionuclides in Imported Rice Samples

Concentrations of Ra-226, Th-228, Ra-228, Th-232 and K-40 in imported rice in Tamale metropolis were also computed and presented (Figure 4.3).

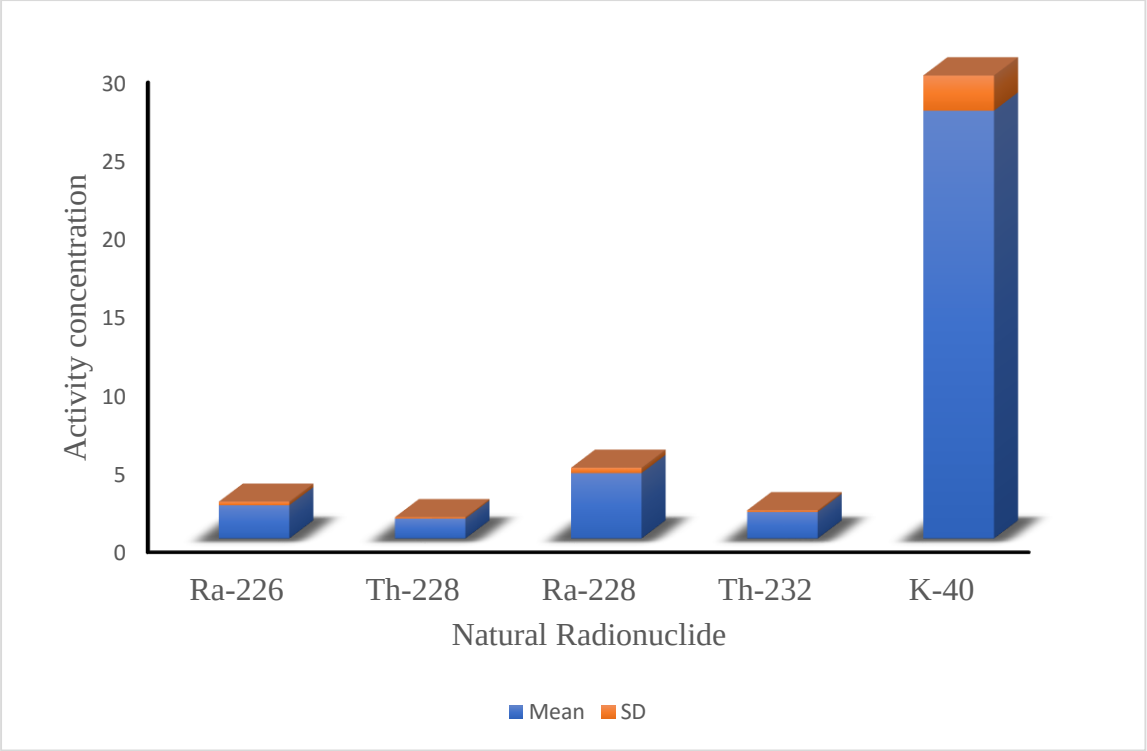

Figure 4.3: A plot of mean activity concentration (Bq/kg) of natural radionuclides in imported rice in Tamale metropolis

The mean activity concentration of Th-228 was found to be between (0.5 ± 0.04 and 2.6 ± 0.21) Bq/kg, with an average of (1.28 ± 0.09) Bq/kg; Ra-228 was found to be between (BDL and 6.4 ± 0.51) Bq/kg, with an average of (4.2 ± 0.34) Bq/kg. With an average of (1.7 ± 0.11) Bq/kg, Th-232 ranged from (0.3 ± 0.02) Bq/kg to (3.5 ± 0.28)

Bq/kg, while K-40 similarly varied from (12.8 ± 1.28 to 60.8 ± 4.8) Bq/kg, with an average of (27.33 ± 2.24) Bq/kg.

K-40 had the highest mean activity concentration and Th-228 had the lowest, in line with the findings of the local rice samples. The comparatively elevated K-40 readings observed can be ascribed to the application of fertilizer in rice farming as well as the prevalence of the radioactive element in plants (Mohammed et al., 2021; Sardans & Peñuelas, 2021).

Concentrations of Th-232 compared to Th-228 and that of Ra-228 compared to Ra-226 followed similar pattern as observed for the local rice. Therefore, the suggested reasons given for the local rice may apply for the imported rice.

Similar to the results for the local rice, the mean concentrations of all natural radionuclides in the imported rice were far below the world average values as per UNSCEAR (2000). This is shown in Figure 4.4 below:

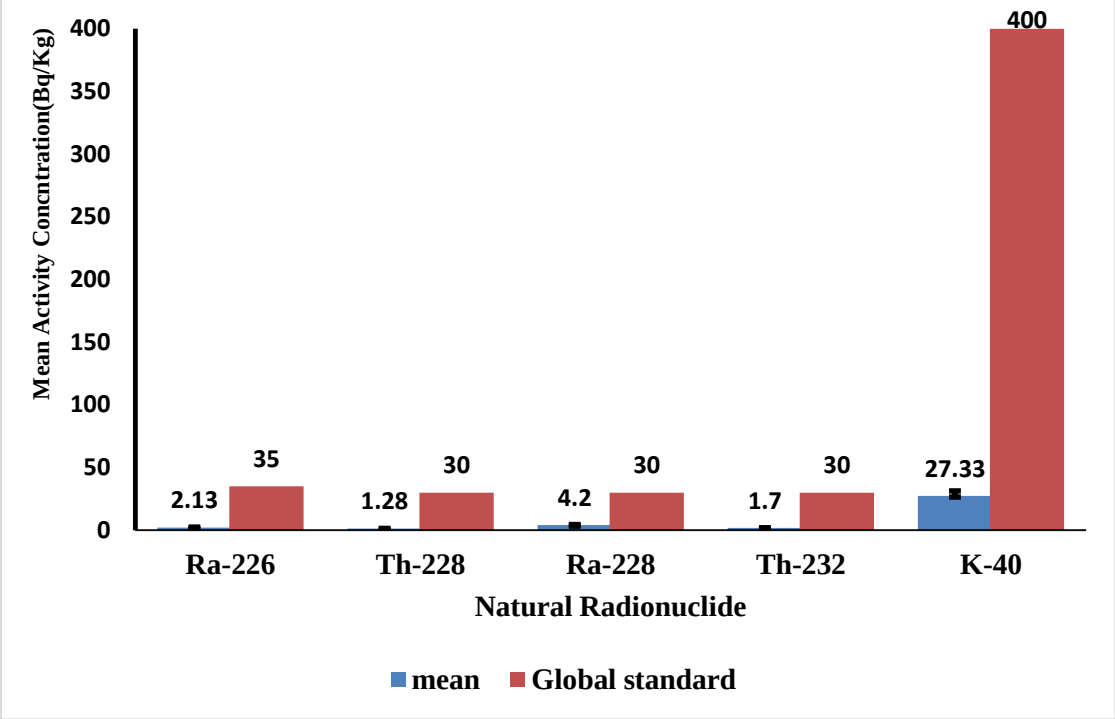

Figure 4.4: A plot of mean activity concentrations (Bq/kg) of natural radionuclides in imported rice in Tamale metropolis compared with the global standard values

As evident in Figure 4.4, the mean activity concentration of K-40 (27.33 Bq/kg) is far lower than the global standard value of 400 Bq/kg. That of Ra-226 (2.13 Bq/kg) is by far lower than the global standard value of 35 Bq/kg, etc.

The far lower values of natural radionuclides in the imported rice compared to global standard values means their presence in the Ghanaian markets do not present any cause for alarm.

Low activity concentrations of radionuclides in food, however, are a cause for concern because human exposure to these substances is not restricted to ingesting

high amounts of radiation at a single, constrained time (acute exposure). A long-term buildup of minute quantities of radioactive materials, such as natural radionuclide concentrations found in the rice samples, can result in chronic radionuclide exposure. Thus, although exposure to low levels of radiation in rice may not have an immediate negative impact on consumers' health, Hong et al. (2019) found that it does contribute slightly to overall health risk over time.

4.3 Comparison of the Concentrations of the Natural Radionuclides in the Local and Imported Rice Samples in Tamale Metropolis

The t-test found no significant variation in the natural radionuclide concentrations between the imported and local rice varieties as evident in Table 4.2:

Table 4.2: T-test comparison (at 95% confidence interval) of activity concentrations of natural radionuclides in rice varieties

Radionuclide	p-value	Remark
^{226}Ra	0.771	NSD
^{228}Th	0.468	NSD
^{228}Ra	0.658	NSD
^{232}Th	0.387	NSD
^{40}K	0.166	NSD

NSD is No Significant Difference

The results obtained from the t-test (Table 4.2) show p-values above 0.05. Thus, based on these p-values, the null hypothesis was accepted. Thus, no significant differences were observed in activity concentrations among the rice samples (local and imported). Statistically, activity concentrations for the rice samples were the same.

A clustered bar chart of the natural radionuclides in local and imported rice was done to have a pictorial view of the differences in their mean concentrations and is shown in Figure 4.5.

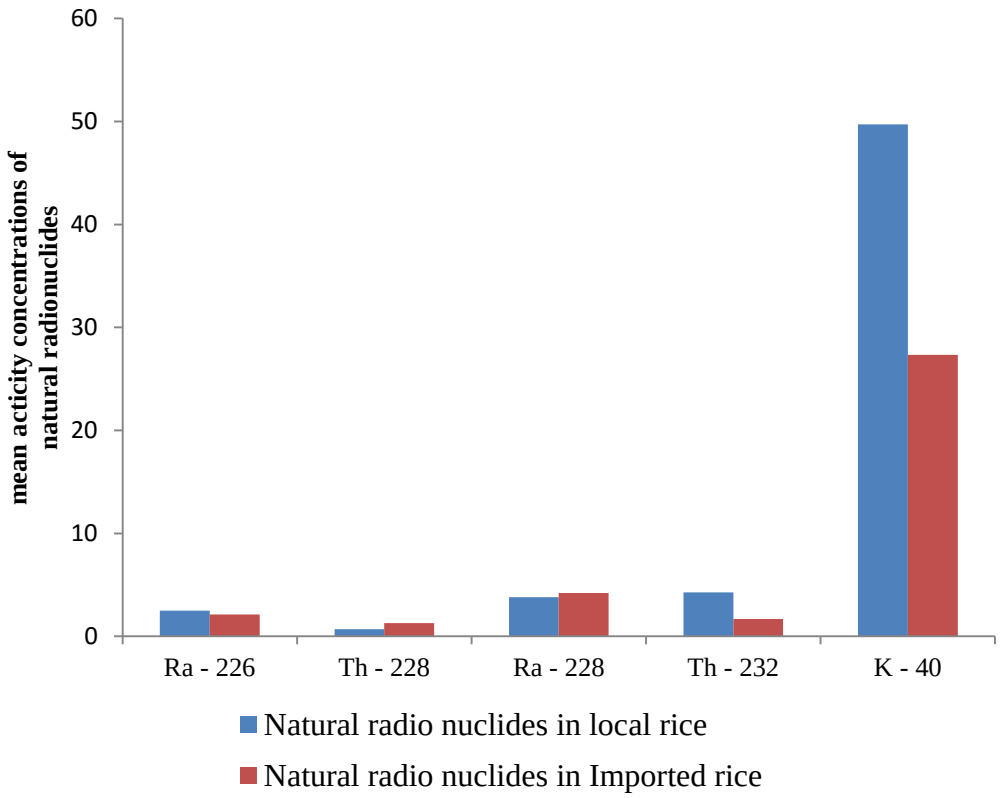

Figure 4.5: A clustered bar chart of mean concentrations of natural radionuclides in local and imported rice in Tamale metropolis.

The clustered bar chart shown in Figure 4.5 indicates pictorially that there are only slight variations in the concentrations of natural radionuclides in local and imported rice in Tamale metropolis.

The slight differences observed suggest that both rice varieties were cultivated under similar geological conditions and similar agricultural practices (e.g. similar soil types,

application of similar fertilizers, application of similar pesticides among others) (Siraz et al., 2023; Jeelani et al., 2022).

Non-significant differences in radionuclides concentrations of local and imported rice varieties suggest that both rice varieties have similar radiological safety. So, consumers who may want to choose rice on the basis of radiological content may choose either.

4.4 External and Internal Hazard Indices

Table 4.3: The external and internal hazard indices in local rice samples

The external and internal hazard indices in local rice samples are presented in Table 4.3.

Sample	External Hazard Index (H_{ex})	Internal Hazard Index (H_{in})
ABL_1	0.0163	0.0191
ABL_2	0.0313	0.0324
CML_1	0.0213	0.0299
CML_2	0.0655	0.0801
Mean	0.0336±0.0222	0.0404±0.0271

The external hazard indices in the local rice samples ranged from 0.0163 to 0.655 and had a mean value of 0.0336, while the internal hazard indices ranged from 0.0191 to 0.0801 with a mean of 0.0404. All values were found to be smaller than unity, suggesting that consumers are not at risk from radioactivity.

Therefore, based on external and internal hazard indices computed, consumers appear to be safe from the negative health outcomes due to the radionuclides. This results is consistent with those of most similar works reported in literature. For example, Najam

et al. (2015) found H_{ex} and H_{in} in rice consumed in Nineveh Province (IRAQ) to be less than unity. Abass and Muttaleb (2018) also found that the H_{in} in canned rice in Iraq was below unity.

Table 4.4: The external and internal hazard indices in imported rice samples

Sample	External Hazard Index (H_{ex})	Internal Hazard Index (H_{in})
ABI_1	0.00536	0.00536
ABI_2	0.0150	0.0245
CMI_1	0.0195	0.0225
CMI_2	0.0320	0.0426
Mean	0.0180±0.0110	0.0237±0.0152

Table 4.4 shows that the imported rice samples had internal hazard indices ranging from 0.00536 to 0.0426 with a mean value of 0.0237. The external hazard indices ranged from 0.00536 to 0.0320 with a mean value of 0.0180. Every sample showed values that were less than unity. These show that the rice samples were not harmful to consumers (Alaboodi et al., 2020).

4.5 Annual Effective Dose Equivalent (AEDE)

Table 4.5: The AEDE for the local and imported rice samples

Local rice sample	AEDE	Imported rice sample	AEDE
ABL_1	0.0315	ABI1	0.0100
ABL_2	0.0562	ABI2	0.0259
CML_1	0.0386	CMI1	0.0341
CML_2	0.1141	CMI2	0.0576
Mean	0.0601±0.0375	Mean	0.0319±0.0198

Table 4.5 presents the findings of the calculation of the estimated AEDE for both the imported and local rice samples. The imported rice's AEDE values ranged from 0.0100 to 0.0576 mSv/y with a mean activity concentration of 0.0319 mSv/y, whereas the local rice's ranged from 0.0315 to 0.1141 mSv/y with a mean activity dose level of

0.0601 mSv/y. These values show that the rice samples surveyed have AEDE below world average (450 mSv/y). These results show that the rice samples (both local and imported) are radiologically safe when the AEDEs were compared with the global recommended permissible limits.

The results is similar to the findings of Hameed et al. (2016) who found the AEDE in rice and salt samples to be below the recommended limits. Arije et al. (2022) also found the mean AEDE to adults from the consumption of rice from Ondo and Ekiti States to be 0.93 and 0.84 mSv/y respectively, which were below the world average of 450 mSv/y.

4.6 Excess Lifetime Cancer Risk (ELCR)

Table 4.6: The ELCR for the local and imported rice samples

Local rice sample	ELCR x 10^{-3}	Imported rice sample	ELCR x 10^{-3}
ABL_1	0.0154	ABI1	0.00494
ABL_2	0.0275	ABI2	0.0140
CML_1	0.0189	CMI1	0.0167
CML_2	0.056	CMI2	0.0282
Mean	0.0295±0.0184	Mean	0.0160±0.0096

After computing the ELCR values for both domestic and imported rice samples, Table 4.6 displays the results. The local rice had ELCR values ranging from 0.0154 x 10^{-3} to 0.0275 x 10^{-3} with a mean of 0.0295 x 10^{-3}, and the imported rice had ELCR values ranging from 0.00494 x 10^{-3} to 0.0282 x 10^{-3} in a mean of 0.0160 x 10^{-3}. The computed ELCR values for both types of rice were less than the permitted limits of radiological danger, which were 0.29×10^{-3} (Arije et al., 2022). Thus the ELCR data

suggest that the probability of developing cancer and its related issues is very low in the lifetime of consumers.

The lower values of the ELCR in this study compared to the world acceptable average of 0.29 x 10^{-3} for radiological risk agrees with most works reported in literature. For example, in a study by Nahar et al. (2018), ELCR values via rice consumption in Bangladesh was found to be less than acceptable limit of 0.29 x 10^{-3} for radiological risk. In Namibia, Onjefu et al. (2020) determined the ECLR values in rice and found that they were below the acceptable limit. Ugbede (2022) found the ECLR values in freshly harvested rice grains in Nigeria to be within the acceptable limit for radiological risk. In another study by Arije et al. (2022), the ELCR values in rice samples from South-western Nigeria were found to be lower than the acceptable world average ELCR value of 0.29 x 10^{-3} for radiological risk.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

This chapter provides a summary of the research findings, a conclusion, and recommendations based on those findings.

5.1 Summary

The concentrations of the natural radionuclides (Ra-226, Ra-228, Th-228, Th-232, and K-40) that were examined in this study were found in local and imported rice that was sold in Tamale city. Due to the quantity of natural radionuclides that have been detected, radiological parameters (ELCR, internal and external hazard indices) were also calculated and utilized to estimate the danger that consumers are likely to face.

Eight samples of rice were gathered from the Tamale Central and Tamale Aboabo markets in the Tamale metropolis four of them were indigenous and the other four were imported. High Purity Germanium (HPGe) Detector was used to prepare and analyze the samples in order to look for naturally occurring radionuclides. The mean activity concentrations of Ra-226, Th-228, Ra-228, Th-232, and K-40 for the local rice (ABL1, ABL2, CML1 and CML2) were 2.5 ± 0.19, 0.7 ± 0.08, 3.8 ±0.40, 4.28 ± 0.34, and 49.73 ± 3.99 Bq/kg, respectively. The mean activity concentrations of Ra-226, Th-228, Ra-228, Th-232, and K-40 for the imported rice (ABI1, ABI2, CMI1 and CMI2) were 2.13 ±0.23, 1.28 ± 0.09, 4.2 ± 0.34, 1.7 ± 0.11, and 27.33 ± 2.24 Bq/kg, respectively. The recorded radioactivity concentrations were below the international recommended values. This suggests that both local and imported rice are

radiologically safe for consumption and consumers would not be exposed to health risks linked to the radionuclides.

The mean concentrations of natural radionuclide contents in the local and imported rice samples did not differ significantly, according to T-test analysis of the concentrations of radionuclides found in the rice samples from the two sources. The average external and internal hazard indices for rice grown locally were 0.0336 and 0.0404, respectively, but the corresponding values for rice imported from elsewhere were 0.0180 and 0.0237. These mean values for both external and internal hazard indices for both local and imported rice were below unity (1). The estimated hazard indices suggest that the rice samples would not have any negative health effects on consumers.

Mean values of ELCR estimated for the local and imported rice samples were 0.0295 x 10^{-3} and 0.0160 x 10^{-3} respectively. These values were below the global average value of 0.29×10^{-3}. The results suggest that both local and imported rice sold in Tamale metropolis may not induce cancer in consumers.

5.2 Conclusion

Activity concentrations of the natural radionuclides (Ra-226, Th-228, Ra-228, Th-232 and K-40) in the local and imported rice sold and consumed in the Tamale metropolis were determined. The estimated mean activity values of Ra-226, Th-228, Ra-228, Th-232 and K-40 were 2.5 ± 0.19, 0.7 ± 0.08, 3.8 ±0.40, 4.28 ± 0.34 and 49.73 ± 3.99 Bq/kg respectively in the local rice whilst 2.13 ±0.23, 1.28 ± 0.09, 4.2 ± 0.34, 1.7 ±

0.11 and 27.33 ± 2.24 Bq/kg occurred in the imported rice brands for Ra-226, Th-228, Ra-228, Th-232 and K-40, respectively.

Mean activity concentrations of detected radionuclides were below the international recommended values. This suggests that both the local and the imported rice are radiologically safe for consumption. The rice may not cause health hazard to consumers.

The current study also found no significant differences in mean activity concentrations of recorded natural radionuclides (Ra-226, Th-228, Ra-228, Th-232 and K-40) between the local and the imported rice brands sold in Tamale metropolis.

Mean values of H_{ex} and H_{in} for the local rice were 0.0336 and 0.0404, respectively while that of the imported rice were 0.0180 and 0.0237, respectively. These mean H_{ex} and H_{in} values estimated for both local and imported rice were below unity (1).

Mean values of AEDE for the local and the imported rice were 0.0601 and 0.0319 mSv/y respectively. These results suggest AEDE values were below 450 mSv/y permitted global average value. The results also showed that rice brands (both local and imported) are radiologically safe for consumption.

The mean values of ELCR estimated for the local and the imported rice samples were 0.0295×10^{-3} and 0.0160×10^{-3}, respectively. These values were also below 0.29×10^{-3} recommended limits as reported by UNSCEAR (2008) and Avwiri et al.

(2016). These values further confirm that both the local and the imported rice are radiologically safe for consumers.

Based on the mean activity concentrations of the detected natural radionuclides (Ra-226, Th-228, Ra-228, Th-232 and K-40), the estimated H_{ex} and H_{in} values, the estimated AEDE and ELCR values recorded for the rice samples, this study concludes that both local and imported rice sold in Tamale metropolis are radiologically safe for consumption. The results of this study could be used as baseline reference for background radionuclide exposure through rice consumption of rice.

5.3 Recommendations

Based on the findings of this work, it is recommended that:

1. Natural radionuclide levels in rice in the metropolis should be monitored for every production season to help determine changes in radionuclide contents emanating from natural or artificial sources.
2. Similar studies should be done for rice produced in other parts of the country (especially, upper East and Volta regions) for comparison with the ones in this study.
3. Investigations on natural radionuclide content should be done on other types of food crops such as maize and especially tuber crops such as yam to help determine radiological implications on people of the metropolis.
4. Other radiological indicators such as radium equivalent activity, gamma index, alpha index, gamma absorbed dose rate and Annual gonadal dose equivalent (AGDE) should be used to determine radiological risk associated with rice consumption in the metropolis.

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APPENDICES

Appendix 1: Analysis of t-test of the activity concentrations of all the radionuclides among the two samples of rice types (local and imported).

Paired T for Ra-226 L - Ra-226 I

	N	Mean	StDev	SE Mean
Ra-226 L	4	2.50	2.28	1.14
Ra-226 I	4	2.13	1.88	0.94
Difference	4	0.38	2.36	1.18

95% CI for mean difference: (-3.38, 4.13)

T-Test of mean difference = 0 (vs not = 0): T-Value = 0.32 P-Value = 0.771

Paired T for Th-228L Th-228I

Th-228L	4	0.700	0.560	0.280
Th-228I	4	1.275	0.971	0.485
Difference	4	-0.575	1.389	0.694

95% CI for mean difference: (-2.785, 1.635)

T-Test of mean difference = 0 (vs not = 0): T-Value = -0.83 P-Value = 0.468

Paired T for Ra-228L Ra-228I

Ra-228L	4	3.80	4.84	2.42
Ra-228I	4	2.10	3.02	1.51
Difference	4	1.70	6.95	3.47

95% CI for mean difference: (-9.35, 12.75)

T-Test of mean difference = 0 (vs not = 0): T-Value = 0.49 P-Value = 0.658

Paired T-Test and CI: Th-232L, Th-232 I

Paired T for Th-232L - Th-232 I

	N	Mean	StDev	SE Mean

Th-232L 4 4.28 4.80 2.40

Th-232 I 4 1.70 1.48 0.74

Difference 4 2.58 5.10 2.55

95% CI for mean difference: (-5.53, 10.68)

T-Test of mean difference = 0 (vs not = 0): T-Value = 1.01 P-Value = 0.387

Paired T-Test and CI: K-40 L, K-40 I

Paired T for K-40 L - K-40 I

	N	Mean	StDev	SE Mean
K-40 L	4	49.7	9.1	4.6
K-40 I	4	27.3	22.6	11.3
Difference	4	22.4	24.6	12.3

95% CI for mean difference: (-16.7, 61.5)

T-Test of mean difference = 0 (vs not = 0): T-Value = 1.82 P-Value = 0.166

Appendix 2: Calculations of external and internal hazard indices in local and imported rice

a. calculation of external hazard index (H_{ex}) in local rice

$H_{ex} = (A_{Ra}/370) + (A_{Th}/259) + (A_K/4810)$

$H_{ex}(ABL1)=1/370 + 0.3/259 + 60/4810$

$= 2.70 \times 10^{-3} + 1.16 \times 10^{-3} + 0.0125 = 0.0163$

$H_{ex}(ABL2)=0.4/370 + 5.8/259 + 37.8/4810$

$= 1.081 \times 10^{-3} + 0.0224 + 7.86 \times 10^{-3} = 0.0313$

$H_{ex}(CML1)=3.2/370 + 0.6/259 + 49.6/4810$

$= 8.65 \times 10^{-3} + 2.32 \times 10^{-3} + 0.0103 = 0.0213$

$H_{ex}(CML2)=5.4/370 + 10.4/259 + 51.5/4810$

$= 0.0146 + 0.0402 + 0.0107 = 0.0655$

b. calculations of internal hazard index (H_{in}) in local rice

$H_{in}= (A_{Ra}/185) + (A_{Th}/259) + (A_K/4810)$

$H_{in}(ABL1)=1/185 + 0.3/259 + 60/4810$

$= 5.41 \times 10^{-3} + 1.16 \times 10^{-3} + 0.0125 = 0.0191$

$H_{in}(ABL2)=0.4/185 + 5.8/259 + 37.8/4810$

$= 2.162 \times 10^{-3} + 0.0224 + 7.86 \times 10^{-3} = 0.0324$

$H_{in}(CML1)=3.2/185 + 0.6/259 + 49.6/4810$

$= 0.0173 + 2.32 \times 10^{-3} + 0.0103 = 0.0299$

$H_{in}(CML2)=5.4/185 + 10.4/259 + 51.5/4810$

$= 0.0292 + 0.0402 + 0.0107 = 0.0801$

c. calculations of H_{ex} in imported rice

$H_{ex} = (A_{Ra}/370) + (A_{Th}/259) + (A_K/4810)$

$H_{ex}(ABI1)=0/370 + 0.7/259 + 12.8/4810$

$= 0 + 2.70 \times 10^{-3} + 2.66 \times 10^{-3} = 0.00536$

$H_{ex}(ABI2)=3.5/370 + 0.3/259 + 21.2/4810$

$= 9.46 \times 10^{-3} + 1.16 \times 10^{-3} + 4.41 \times 10^{-3} = 0.0150$

$H_{ex}(CMI1)=1.1/370 + 3.5/259 + 14.5/4810$

$= 2.97 \times 10^{-3} + 0.0135 + 3.01 \times 10^{-3} = 0.0195$

$H_{ex}(CMI2)=3.9/370 + 2.3/259 + 60.8/4810$

$= 0.0105 + 8.88 \times 10^{-3} + 0.0126 = 0.0320$

d. calculation of H_{in} in imported rice

$H_{in}= (A_{Ra}/185) + (A_{Th}/259) + (A_K/4810)$

$H_{in}(ABI1)=0/185 + 0.7/259 + 12.8/4810$

$= 0 + 2.70 \times 10^{-3} + 2.66 \times 10^{-3} = 0.00536$

$H_{in}(ABI2)=3.5/185 + 0.3/259 + 21.2/4810$

$= 0.0189 + 1.16 \times 10^{-3} + 4.41 \times 10^{-3} = 0.0245$

$H_{in}(CMI1)=1.1/185 + 3.5/259 + 14.5/4810$

$= 5.95 \times 10^{-3} + 0.0135 + 3.01 \times 10^{-3} = 0.0225$

$H_{in}(CMI2)=3.9/185 + 2.3/259 + 60.8/4810$

$= 0.0211 + 8.88 \times 10^{-3} + 0.0126 = 0.0426$

Appendix 3: Calculations of absorbed dose rate (D) in local rice

$D= 0.49A_{Ra} + 0.76A_{Th} + 0.048A_K$

D(ABL1)= 0.49 x 1 + 0.76 x 0.3 + 0.048 x 60 = 3.598

D(ABL2)= 0.49 x 0.4 + 0.76 x 5.8 + 0.048 x 37.8 = 6.418

D(CML1)= 0.49 x 3.2 + 0.76 x 0.6 + 0.048 x 49.6= 4.405

D(CML2)= 0.49 x 5.4 + 0.76 x 10.4 + 0.048 x 51.5 = 13.02

Appendix 4: Calculations of Absorbed dose rate (D) in imported rice

$D = 0.49A_{Ra} + 0.76A_{Th} + 0.048A_K$

D(ABI1)= 0.49 x 0 + 0.76 x 0.7 + 0.048 x 12.8 = 1.146

D(ABI2)= 0.49 x 3.5 + 0.76 x 0.3 + 0.048 x 21.2 = 3.265

D(CMI1)= 0.49 x 1.1 + 0.76 x 3.5 + 0.048 x 14.5 = 3.895

D(CMI2)= 0.49 x 3.9 + 0.76 x 2.3 + 0.048 x 60.8 = 6.577

Appendix 5: Calculations of Annual Effective Dose Equivalent (AEDE) in local rice

AEDE ($mSvyr^{-1}$) = D (nGy/hr) x 8760 (hr) x 0.7 (Sv/Gy) x 0.2 (yr^{-1}) x 10^{-6}

Note that the units will cancel out, leaving $nSvyr^{-1} = 10^{-9}$ x $Svyr^{-1}$ =10^{-6} x 10^{-3} x $Svyr^{-1}$ = 10^{-6} x $mSvyr^{-1}$. So, x 10^{-6} is added in the equation to leave the unit of ELCR as $mSvyr^{-1}$.

AEDE(ABL1)= 3.598 x 8760 x 0.7 x 0.2 x 10^{-6} = 4.41 x 10^{-3}

AEDE(ABL2)= 6.418 x 8760 x 0.7 x 0.2 x 10^{-6} = 7.87 x 10^{-3}

AEDE(CML1)= 4.405 x 8760 x 0.7 x 0.2 x 10^{-6} = 5.4 x 10^{-3}

AEDE(CML2)= 13.02 x 8760 x 0.7 x 0.2 x 10^{-6} = 0.0160

Appendix 6: Calculations of Annual Effective Dose Equivalent (AEDE) in imported rice

AEDE ($mSvyr^{-1}$) = D x 8760 x 0.7 x 0.2 x 10^{-6}

AEDE(ABI1)= 1.146 x 8760 x 0.7 x 0.2 x 10^{-6} = 1.41 x 10^{-3}

AEDE(ABI2)= 3.265 x 8760 x 0.7 x 0.2 x 10^{-6} = 4.00 x 10^{-3}

AEDE(CMI1)= 3.895 x 8760 x 0.7 x 0.2 x 10^{-6} = 4.78 x 10^{-3}

AEDE(CMI2)= 6.577 x 8760 x 0.7 x 0.2 x 10^{-6} = 8.07 x 10^{-3}

Appendix 7: Calculations of Excess Lifetime Cancer Risk (ELCR) in local and imported rice

a. calculations of ELCR in local rice

Excess Lifetime Cancer Risk was calculated using equation 4:

ELCR=AEDE ($mSvyr^{-1}$) x DL (yr) x RF (Sv^{-1}) x 10^{-3}……(4)

Note that the units will cancel out, leaving only mili (m). So, x 10^{-3} is added to take away the m, leaving ELCR with no unit.

ELCR(ABL1) = 4.41 x 10^{-3} x 70 x 0.05 x 10^{-3} = 0.0154 x 10^{-3}

ELCR (ABL2) = 7.87 x 10^{-3} x 70 x 0.05 x 10^{-3} = 0.0275 x 10^{-3}

ELCR (CML1) = 5.4 x 10^{-3} x 70 x 0.05 x 10^{-3} = 0.0189 x 10^{-3}

ELCR (CML2) = 0.0160 x 70 x 0.05 x 10^{-3} = 0.056 x 10^{-3}

b. calculations of ELCR in imported rice

ELCR (ABI1) = 1.41 x 10^{-3} x 70 x 0.05 x 10^{-3} = 0.00494 x 10^{-3}

ELCR (ABI2) = 4.00 x 10^{-3} x 70 x 0.05 x 10^{-3} = 0.0140 x 10^{-3}

ELCR (CMI1) = 4.78 x 10^{-3} x 70 x 0.05 x 10^{-3} = 0.0167 x 10^{-3}

ELCR (CMI2) = 8.07 x 10^{-3} x 70 x 0.05 x 10^{-3} = 0.0282 x 10^{-3}

Appendix 8: Analysis of rice samples report

RADIATION PROTECTION INSTITUTE
GHANA ATOMIC ENERGY COMMISSION

Incase of reply the number and date of this letter should be quoted

Our Ref: RPI/CTC.6/88
Your Ref:

Date: 15th June, 2022

The Director
Akenten Appiah Menka University
Of Skills Training & Entrepreneurial Dev.
(AAMUSTED)
Asante Mampong

Attn: Mr. Timothy Konlan Nunifant

Dear Sir,

RE: REQUEST TO COUNT AND ANALYSE RICE SAMPLE - REPORT

Pleased to forward the attached report on the above subject matter to you for your needed attention.

Thank you.

Yours faithfully,

Esther B. Tetteh-Mensah (Mrs.)
Administrative Officer
for: **DIRECTOR**

Encls .

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ENVIRONMENTAL RADIATION PROTECTION CENTRE (ERPC)

SAMPLE ANALYSIS REPORT

DETAILS OF INSTITUTION AND TEST	
Name of Institution (Client)	Timothy Konlan Nunifant
Address (Company/Institution/Client)	Akenten Appiah Menka University of Skills Training and Enterpreneural Development (AAMUSTED), Asante Mampong
Contact Person Tel. E-mail	Timothy Konlan Nunifant +233209123779 nunifant@gmail.com
Type of Test	Rice Samples Analysis
Type of Sample	Rice Grains
Test Number	ABI1, ABL1, ABL2, ABI2, CMI1, CML1, CMI2 and CML2
Test Date	20/05/22
Job Number	RGR-2022
Report Date	7/06/2022

Radiation Protection Institute
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TEST RESULTS

RADIOACTIVITY MEASUREMENT, RICE GRAINS

SAMPLE ID	Ra-226 (Bq/Kg)	Th-228 (Bq/Kg)	Ra-228 (Bq/Kg)	Th-232 (Bq/Kg)	K-40 (Bq/Kg)
ABI1	DL	1.40 ± 0.07	DL	0.7 ± 0.04	12.8 ±1.28
ABL1	1.0 ± 0.05	DL	0.5 ± 0.03	0.3 ± 0.02	60 ± 4.8
ABL2	0.4 ± 0.03	1.1 ± 0.09	10.5 ± 0.84	5.8 ± 0.46	37.8 ± 3.02
ABI2	3.5 ± 0.28	0.6 ± 0.05	DL	0.3 ± 0.02	21.2 ± 1.70
CMI2	3.9 ± 0.31	2.6 ± 0.21	2.0 ± 0.16	2.3 ± 0.18	60.8 ± 4.8
CML2	5.4 ± 0.43	0.5 ± 0.04	4.2 ± 0.34	10.4 ± 0.83	51.5 ± 4.12
CMI1	1.1 ± 0.09	0.5 ± 0.04	6.4 ± 0.51	3.5 ± 0.28	14.5 ± 1.16
CML1	3.2 ± 0.26	1.2 ± 0.10	DL	0.6 ± 0.05	49.6 ± 4.01

*DL = Detection Limit

Report prepared by:

LILIAN AGYEMAN
PRINCIPAL TECHNOLOGIST
ERPC LABORATORY

Reviewed by:

DR. OSCAR K. ADUKPO
MANAGER, ERPC

Approved by:

DR. ERIC T. GLOVER
DIRECTOR, RADIATION PROTECTION INSTITUTE

Radiation Protection Institute
Ghana Atomic Energy Commission
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