RADIOACTIVITY IN FARM SOILS AND FOOD CROPS GROWN IN JOS AND ABEOKUTA, NIGERIA AND ITS ASSOCIATED CANCER RISKS

BY

SHAMSIDEEN KUNLE ALAUSA

B. Sc Hons. (Ogun); M. Sc. Physics (Ibadan)

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CERTIFICATION

I certified that the work described in this thesis was carried out under my supervision by MR. SHAMSIDEEN KUNLE ALAUSA in the Department of Physics, University of Ibadan.

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SUPERVISOR

N. N. Jibiri
B.Sc. (Jos), M.Sc, Ph. D (Ibadan)
Senior Lecturer, Department of Physics
University of Ibadan, Nigeria.

DEDICATION

To

Late Mrs. Sikirat Alausa for sending me to school to attain western education

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ABSTRACT

Ionizing radiations resulting from either natural or artificial radioactivity are useful but associated with them are health risks which increase with exposure. The natural radioactivity levels in soils of some locations in Jos and Abeokuta are significantly higher than the world average. Enhanced internal and external radiation exposures to man may result from physical presence in, and ingestion of food items grown in these areas. Scientific data are sparse on the radionuclide contents in food crops, farm soils and their radiological implications on the population. Therefore the aim of this study was to determine the radioactivity levels of ^{40}K, ^{226}Ra and ^{232}Th in food crops and farm soils, and associated cancer risks in the population in the areas.

A total of 243 food crop samples from 19 commonly grown types including acha, cowpea, cassava, cocoyam, Guinea corn, maize and yam; and 106 soils samples were randomly collected from 40 farm lands, 23 in Jos and 17 in Abeokuta, selected at random. The samples were air dried to constant mass, pulverized, sieved to pass 2mm mesh-size and sealed for 4 weeks to attain secular equilibrium. The activity concentration of the radionuclides were determined by counting each sample for 10 hours using a gamma-ray spectrometer comprising 76mm x 76mm NaI(TI) detector coupled to a multichannel analyzer. The effective dose rates due to ingestion of the food crops and outdoor effective dose rates due to farm soils were evaluated using the calculated activity concentrations and food consumption rates from Federal Office of Statistics, Nigeria. The risk of incurring cancer from radiation exposure were evaluated using carcinogenicity radionuclide slope factors by United States Environmental Protection Agency and the linear non-threshold radiation risk model, and compared with the International Commission on Radiological Protection (ICRP) recommended limits. Data were analyzed using descriptive statistics.

The concentration of ^{40}K, ^{226}Ra and ^{232}Th in food crops in Jos ranged from 8.7-1406.1, 2.1-85.5 and 2.6-89.8 $Bqkg^{-1}$ respectively; whereas in Abeokuta the range was 38.2-1648.3, 2.1-81.1 and 2.6-48.3 $Bqkg^{-1}$ respectively. The concentration of ^{40}K, ^{226}Ra and ^{232}Th in farm soils were respectively 698.0±416.0; 143.1±80.8 and 287.3±306.3 in Jos and 411.0±341.0; 65.0±29.0 and 184.0±205.0$Bqkg^{-1}$ in Abeokuta. The radioactivity levels were higher in Jos than Abeokuta. The tin mining in Jos might be the principal differential factor for its elevated radioactivity compared to Abeokuta. The annual average effective doses due to food ingestion in Jos was 0.2±0.01μSv (cowpea), 1852.0±43.1μSv (yam); in Abeokuta 58.7±15.7μSv (cocoyam) and 1064.6±32.2μSv

(cassava). The average annual outdoor effective doses from farm soils were 0.43±0.32mSv for Jos and 0.21±0.18mSv for Abeokuta. The cancer risks due to farm soils and food ingestion were 1.42 x 10^{-2} and 8.57x10^{-3} for Jos and Abeokuta respectively. The effective doses were below the ICRP recommended limit of 1mSv and the cancer risks were slightly higher than the ICRP value of 1.0 x10^{-3}.

Cassava and yam had high radioactivity compared to other food crops. Radiological cancer risk among the population was high. The quantity of cassava and yam consumed from the areas should be reduced.

Keywords: Radioactivity, Ingestion effective dose, Cancer risk.

Word count: 499

CHAPTER ONE
INTRODUCTION

1.1 Sources of Ionizing Radiation in the Environment

1.1.1 Natural sources of radiation

The natural sources of radiation are either terrestrial (primordial radionuclides) or extra-terrestrial (cosmic rays) and cosmogenic radionuclides. These sources are briefly discussed below.

1.1.1.1 *Terrestrial sources of Ionizing Radiation:*

Radiation from the primordial sources constitutes about 85% of the natural background radiation exposure received by individuals in the environment (IAEA 1996, Obed et al., 2005). About 70 out of 340 naturally occurring nuclides on earth are radioactive thus man is continually exposed to radiation due to natural radioactivity in the terrestrial environment (Olomo, 2006). The specific activity levels of terrestrial sources of radiation are related to the composition of each lithological area and to the content of the rock from which the soils originate (Akhtar, 2004 and Tahir, 2005).

1.1.1.2 *Radioactivity decay series:*

There are four naturally occurring radioactive decay series (Table 1.1). These are Thorium (^{232}Th), Neptunium (^{237}Np), Uranium (^{238}U) and Actinium (^{235}U), each with atomic mass, A which takes the form of 4n, 4n+1, 4n+2 and 4n + 3 respectively; where n is an integer. The members of natural radioactive series are genetically related by alpha decay (Ghoshal, 2005; Sanni *et al.,* 1985). The longest lived member in the Neptunium series has a half-life of 2.2×10^6 years which is three orders of magnitude shorter than the age of the earth thus the series no longer exist in nature. The other three series have sufficiently long lived radionuclides to survive till the present time and are still found in varying amounts in the earth crust.

Potassium – 40 (^{40}K) is another naturally occurring radionuclide with half-life, $T_{1/2,}$ of 1.3×10^9 years. It is an important biogenic non-series radionuclide (ICRP, 1976; Lan and Weng, 1989) and constitutes a small fraction of about 0.0118 % of the natural potassium but it makes a significant contribution to radioactivity in the environment and

Table 1.1: Natural radioactive decay series (Tait, 1980)

Name of series	Type	Stable end product	Parent radionuclide	Half-live (years)
Thorium	4n	^{208}Pb	^{232}Th	$1.30x10^{10}$
Neptunium	4n+1	^{209}Bi	^{237}Np	$2.20x10^{6}$
Uranium	4n+2	^{206}Pb	^{238}U	$4.47x10^{9}$
Actinium	4n+3	^{207}Pb	^{235}U	$7.1x10^{8}$

in the living tissues. Potassium is widely distributed in nature, with abundances of about 0.1% for limestone, 1.0% for sandstones and as much as 3.5% for some granite (NCRP, 1991).

The other sources of terrestrial exposure are from ^{222}Rn and its daughter products; ^{210}Pb and ^{210}Po which usually got attached to moisture or dust particles in the atmosphere. The daughter products in most natural radioactive transformations are themselves unstable and hence, the process of radioactivity continues until a stable end product is formed. Each chain of such successive decay constitutes a radioactive series (Figures. 1.1 and 1.2). In recent years, the environmental radiation exposure has been augmented by human activities that could enhance the redistribution of naturally occurring radionuclides. A major contribution to the increase of environmental radiation exposure is a result of human activities such as mining and milling operations (Lalit et al., 1982; Babalola, 1984; Oresegun and Babalola, 1993). The radionuclides in food crops are derived from the radionuclides in the earth crust.

1.1.1.3 *Extra-terrestrial sources of Ionizing Radiation:*

The highly energetic cosmic rays with energies in the range between 10^2 MeV and 10^{14} MeV continually bombard the earth from the outer space. Cosmic radiation consists of a mixture of protons (87%), alpha-particles (11%), electrons (1%) and a trace of heavier nuclei (1%) (Sabol and Weng, 1995; Adams and Allday, 2000). The mechanism for the production of the cosmic rays is not known but the origin of the rays is deep in the interstellar space. Cosmic rays according to Jibiri (2000); Farai and Jibiri (2000a); and Farai and Obed (2006) are the major sources of ionizing in the atmosphere from altitude 70 km to 1 km, below which the ionizing effect is comparable to that from airborne and terrestrial radiation. The interaction of cosmic rays with atoms and molecules of the upper atmosphere results in the production of ^{14}C, ^{7}Be and ^{3}H, referred to as cosmogenic radionuclides. The contribution of cosmic rays to the environmental radiation exposure is about 15% of the natural background radiation.

1.2 Man-made sources of radiation

In the environment due to technological advancement and research more radiation sources other than the natural sources are now available in the environment. Such advancement include the successful development of radiation facilities which can be employed for diagnostic radiology (Farai, 2011); irradiation of food for the control and

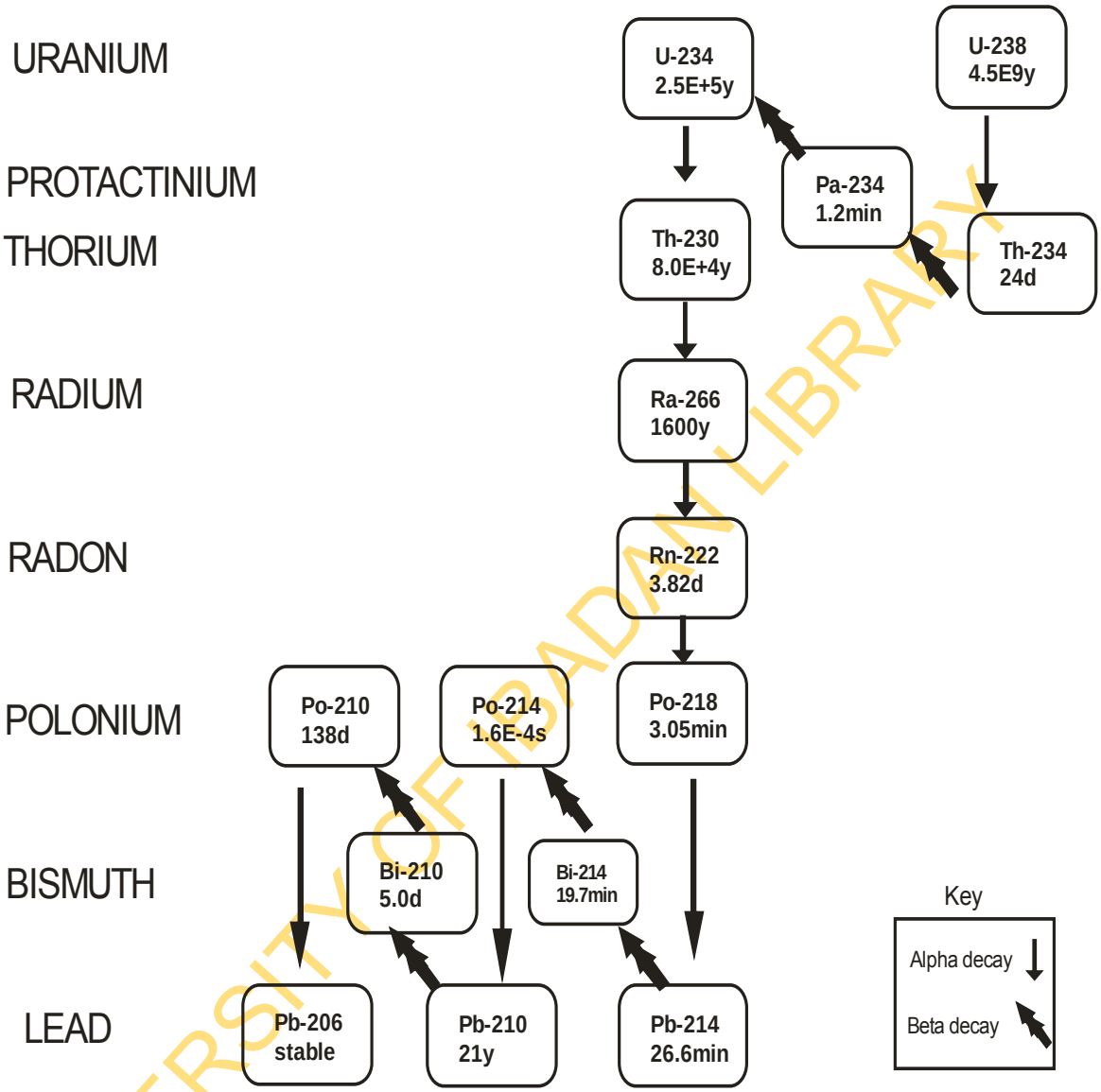


Fig. 1.1: Uranium Decay Series (After NCRP, 1976)

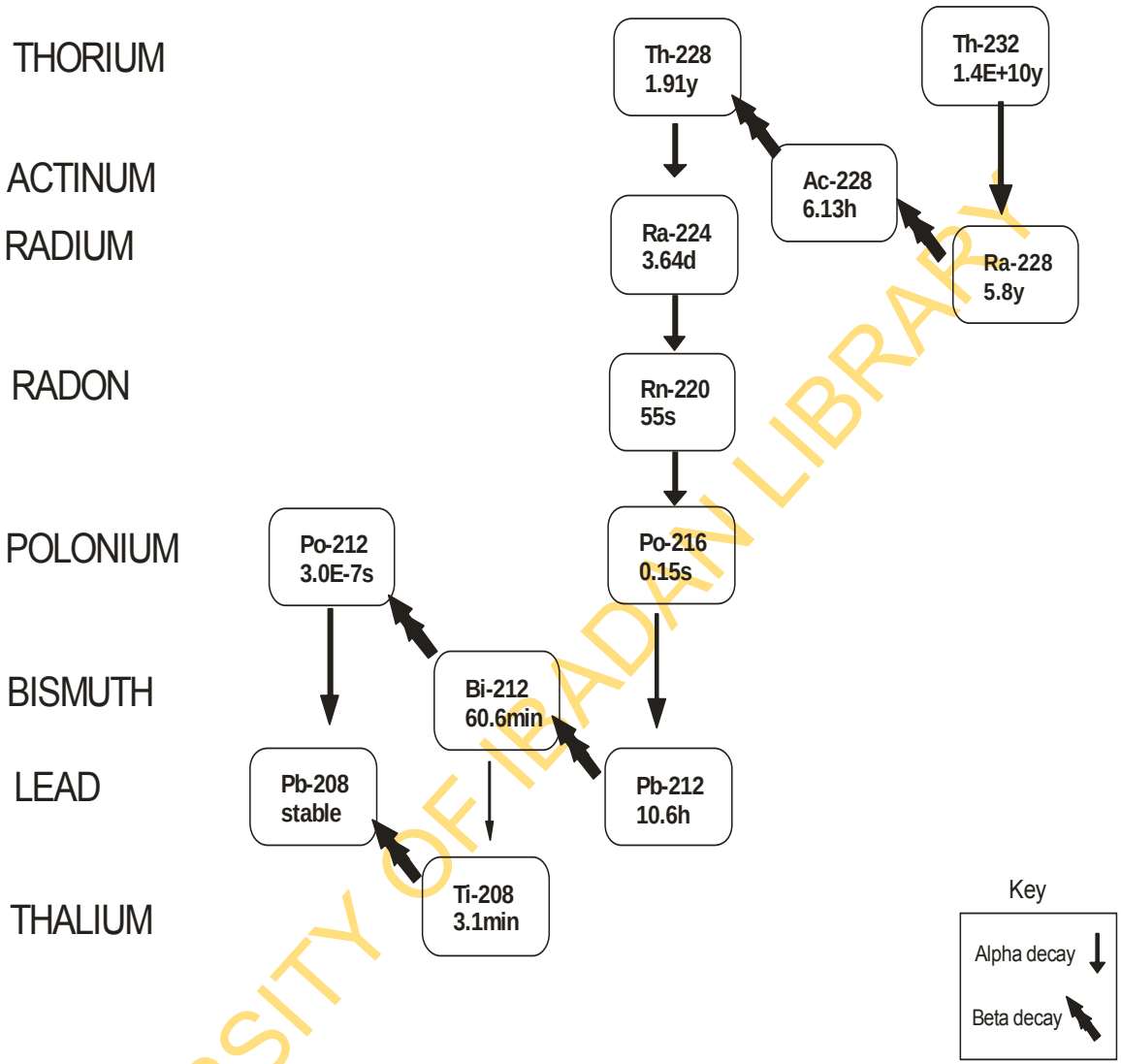


Fig. 1.2: Thorium Decay Series (After NCRP, 1976)

prevent rotting (Lembke et al., 1995); and irradiation of seeds to aid germination and early maturity in fruit production (Jibiri et al., 2005). Man-made sources of radiation also include

radiation generating devices such as x-ray machine for medical diagnosis and therapy and nuclear accelerators for the study of nuclear transmutations. Other sources are nuclear reactors for energy production and nuclear weapons for warfare. Significant contamination of the environment may occur when the source in these applications are not properly managed or handled. A typical example is the major nuclear accident at the Chernobyl-4 nuclear power installation in 1986 when huge amounts of various radionuclides escaped into the atmosphere (Olomo, 2006). Other important man-made radionuclides are strontium-90 (^{90}Sr), iodine-131 (^{131}I), caesium-137 (^{137}Cs) and americium-241 (^{241}Am) (Hernandez et al., 2004). It has been reported that, out of the total radiation dose that the world population receives, about 96.1% is from natural sources and the remaining 3.9% is from man-made sources. (Chougankar et al., 2003 and Shiva et al., 2008)

1.3 Biological Effect of Radiation

When ionizing radiation transverses any medium, it releases all or part of its energies to the electrons in the medium thereby causing ionization. The effect of radiation and the subsequent health effects if it interacts with any biological entity are due to physical and chemical changes that result from the ionization. The basic building blocks of human body are the cells that form tissues and organs. A unit cell in human body consists of a nucleus, which is surrounded by about 70% colourless fluid called cytoplasm that contains variety of compounds like salts, carbohydrates, fats, amino acids and proteins. A cell is injured when exposed to radiation which eventually interacts with other non-irradiated cells and thereby causing damage to the entire biological entity. The injury incurred by the cell as a result of exposure to ionizing radiation may lead to molecular changes and formation of chemical species or radicals (H^+ and OH^-) which have deleterious effects on the chromosomes materials of the cells. The OH^- and H^+ attack Deoxyribonucleic Acid (DNA) causing the breakage of the molecules and the rupturing of the molecular bonds. The breakage of the DNA molecules ends up to a sudden random change in genetic code, and as a consequence causes genetic mutation. Such mutated cells may be repaired in a process called DNA degeneracy. Mutated cells that are not properly repaired may die through apoptosis or survive as viable but transferred from a parent to an offspring. The effects of radiation exposure of human (multi-cellular organism) cells are

complicated. The water content in the cell experiences ionization and excitation within 10^{-16} second when radiation transfers energy to a biological medium. The resulting ions interact with other water molecule and cause a number of new products like OH^-, H^+ and strong oxidizing agent H_2O_2, (hydrogen peroxide). Figure 1.3 shows the chains of event that could take place after a cell is exposed to ionizing radiation. The biological effect of radiation actually depends on the dose, type of radiation and the radiosensitivity of the cell. The biological effects of radiation can be broadly categorized into stochastic and deterministic effects.

Stochastic effects include malignant and hereditary diseases for which the probability of an effect occurring rather than its severity is considered to be directly proportional to the effective dose level. In stochastic effects, any radiation dose no matter how small is capable of initiating an effect. Genetic mutations are examples that can result from stochastic effects. A gene mutation occurs when the Deoxyribonucleic Acid (DNA) is altered. In 1927, Mueller discovered the mutagenic properties of ionizing radiation and reported that radiation can cause alteration to the genetic information contained in a germ cell. Genetic mutation caused by radiation exposure can be transferred from a parent to an offspring. If the mutant gamete is successfully fertilized and the zygote (fertilized ovum) develops into a live offspring, then the mutation is carried into the progeny. Radiogenic cancer is a stochastic effect of ionizing radiation and the risk of incurring cancer from radiation exposure depends on factors like, the dose administered over time, the age, sex and genetic background of the exposed person. In recent time, cancer has assumed greater importance in the health agenda throughout the world and it has been observed that exposure to ionizing radiation increases the risk of incurring cancers (Farai, 1993, Brenner et al., 2003).

Deterministic effect of radiation is predictable and its severity is an inevitable consequence of exceeding a given threshold radiation dose. In other word the severity of the deterministic effect is a function of radiation dose. Examples of deterministic effects are non-malignant skin damage (erythema), and hematological effects (changes in the composition of the blood). Somatic effect is deterministic and may be observed when an individual is irradiated. The damage due to somatic effect is only limited to the exposed individual, and in essence the individual suffers and dies with the damage. Somatic effects may take a longer time to develop and become evident after ionizing radiation had been administered either acutely or over an extended period.

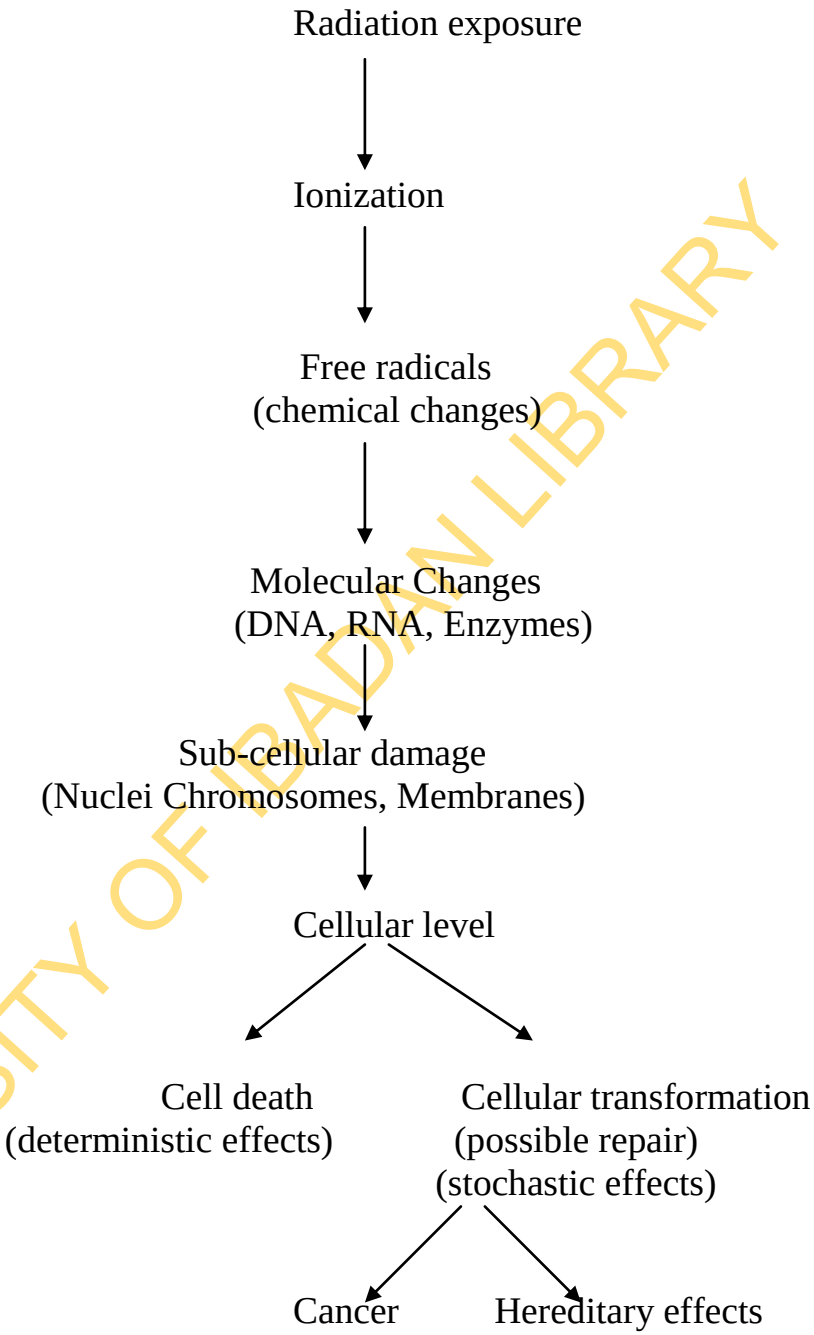


Figure 1.3 Chains of events in a cell after exposure to ionizing radiation.

This is referred to as delayed somatic effect. Another delayed somatic effect is cataract which affects the opacity of the lens of the eye. A radiogenic cataract is a deterministic effect because there is a practical threshold of ionizing radiation dose below which cataract is not produced or manifested; and its severity, when it occurs, is related to the magnitude of the radiation dose and the time over which it is administered.

1.4 Geographical and Geological descriptions of the study areas

1.4.1 Jos

Jos (Lat. 7^{o} 45' N to 12^{o} 00'N and Long. 7^{o} 32' E to 11^{o} 10' E) is located on a granite plateau about 1100m above sea level in the north central part of Nigeria. (Badejoko, 1975). The lithological formation of Jos consists of a basement complex, biotite and new basalts (Badejoko, 1975; Oshin and Rahaman, 1986; Rahaman, 1988). Jos is characterized by a near temperate climate on the Plateau and a hot humid climate on the lower parts. Generally the weather conditions comprise warm rainy season (April-October) and much colder Harmattan period (December- February). The mean annual temperature in the Jos ranges between 20^{0}C and 25^{0}C while the mean annual rainfall figures range from 131.75 cm in the southern part to 146.00 cm on the Plateau. Extraction and smelting of tin in Northern Nigeria was small scale local business before 1904 when prospectors from Niger Company discovered the source of cassiterite in the alluvium of rivers draining the granite complexes of the Bisichi-Bukuru-Ropp area of the Jos. With the discovery of the source area, commercial exploitation of the deposits began immediately (Alexander, 1996 and Alexander and Kidd, 2000).

The geological map of Nigeria showing the lithological formation of Jos Plateau with its associated tin mining fields is shown in Figure 1.4. Tin and columbite-ores are found in commercial quantities in the Jos-Plateau. The ores are usually associated with gneisesnized biotite granite. The gneiss granite is known to contain radioactive elements such as uranium, potassium, and thorium in varying concentrations (Cothern and Lappenbusch, 1983). The abundance of the tin mineral in commercial quantity led to the exploration and mining activities in the area that commenced in 1904 (Oresegun and Babalola, 1990; Oresegun and Babalola, 1993).

During the World War II, commercial production of tin rose to a peak of about 17000 tons per year. The major areas involved in the commercial exploration and mining activities of the tin ore for more than 50 years are Bisichi, Bukuru, Ropp Dorowa-Bababuje, Dorowa-Tsoho, etc but the large scale mining activity takes place in Bisichi in

Barkin Ladi local government council of Jos-Plateau (Jibiri and Agomuo, 2007). The land area degraded as a result of mining activity is shown in Figure 1.5.

Because of the mining activities, most accessible deposits were exhausted and significant surface devastation was caused, leading to abandoned pits and ponds, soil erosion, deforestation, and altered surface drainage (Figure 1.5) (Ogezi, 2005). However the informal (illegal) tin ore mining is still carried out by local miners who use unsafe and crude surface or underground mining and processing methods (Alexander, 1996; Pasquini and Alexander, 2005). As a result of mining activity, about 320 square kilometers of agricultural farm lands were disrupted and disturbed (Pasquini and Alexander, 2005). Consequently the farmers used phosphate fertilizers to supplement the nutrients in the farm lands and increase their annual yield of food crops. The application of fertilizers augments the natural radionuclides in the earth crust and environmental radiation levels (El-Bahi et al., 2004). The soil accumulation of Uranium, Thorium and Radium radionuclides can be related to application of phosphoric fertilizers. Low applications may build up to undesired concentrations in the soil, especially when fertilizers with high heavy metal or rare earth element are used (El-Ghawi et al., 1999; Mortevedt, 1992; Pantelica and Salagean, 1997; Spiridon et al., 1995). However the use of phosphate fertilizers on agricultural farms enhances gamma-ray activity concentrations of ^{40}K, ^{226}Ra and ^{232}Th (Nasim et. al 2007)

It was in 1974 that the radioactive nature of the tin-ore and its tailings was realized (Babalola, 1984 and Sanni et al., 1985). Before 1974, the tailings were treated as non-radioactive and as such used in building construction, farming and industrial furnace blasting. During the milling of the tin-ore to obtain, columbite, monazite, zicrcon and ilemenite, including electrostatic and magnetic separations and manual processing methods in the open, dust was usually produced, which was widely dispersed into the environment. This led to the legacy or phenomenon of polluted water supplies, impoverished agricultural farmland, and soil that are found to contain high naturally radioactive elements above normal levels (Babalola, 1984 and Omosaiye, 2001). Oresegun and Babalola (1990) and Ademola, (2008b) reported that the tin processed wastes (tailings) littered the surroundings of the mining sites areas and this would have great influence in the environments with respect to radiation exposure to the population.

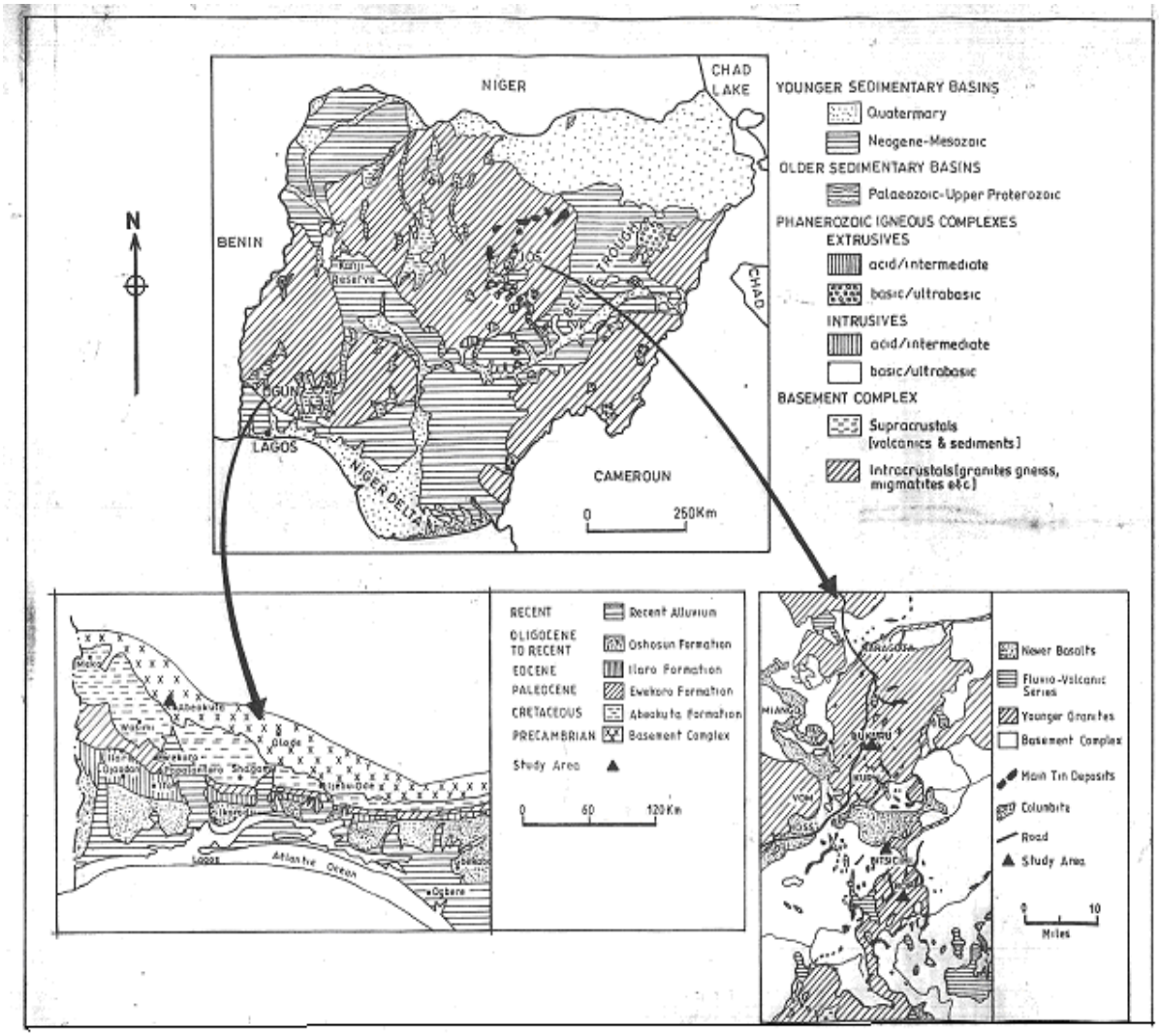


Fig 1.4: Geological map of Nigeria showing the rock distributions in Abeokuta, and Jos-Plateau with its associated tin fields.

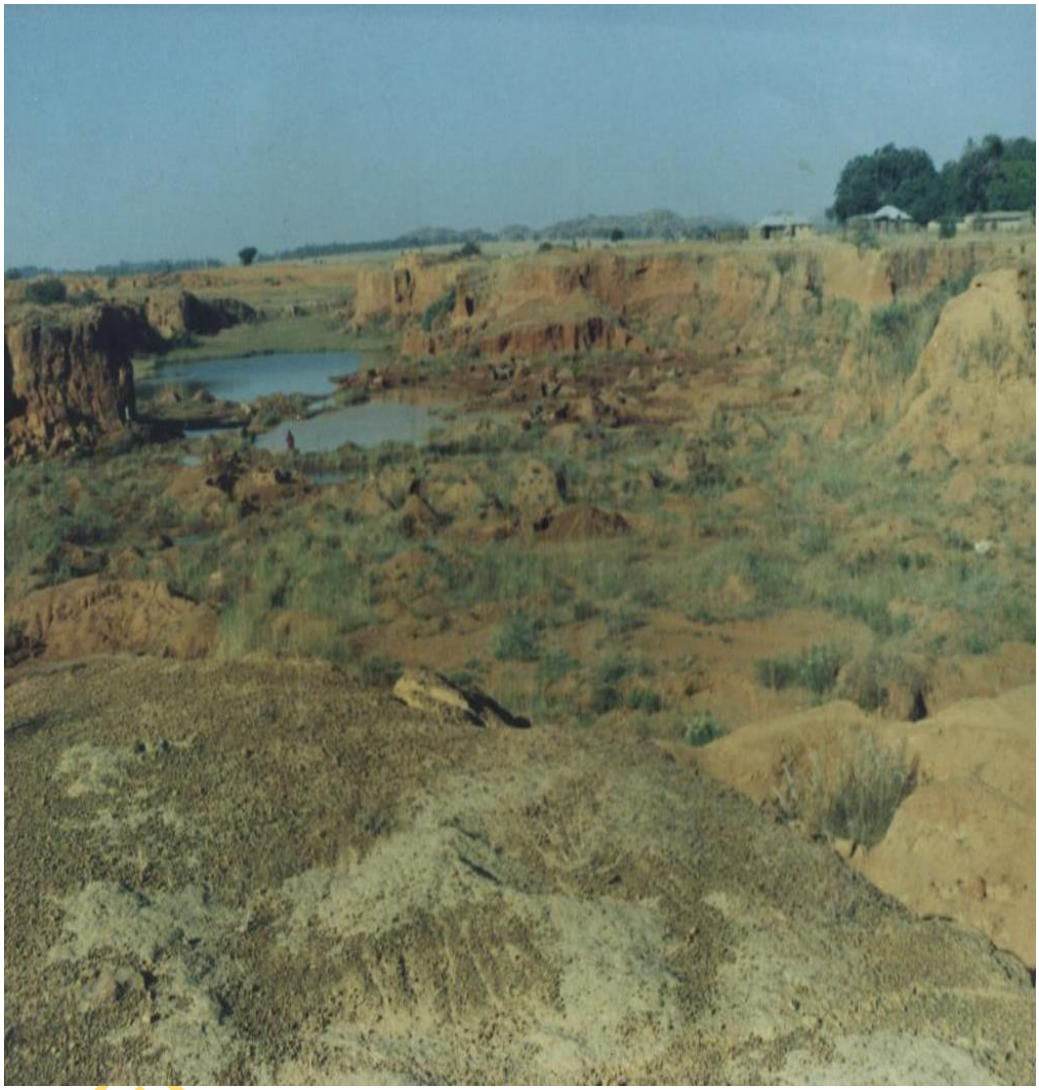


Fig 1.5: Typical mining field in Jos-Plateau

1.4.2 Abeokuta

Abeokuta lies in the latitude 7.1^0 North of the Equator and longitude 3.2^0 East of the Greenwich Meridian. The relief is characterized by escarpments which rise from the river plain to a height of approximately 150 m above the sea level in the west and in the southern and northern plains. The eastern and southern regions are characterized by deeply dissected hills rising to approximately 180 m above sea level (Adejuwon and Adeniyi, 2011). Abeokuta enjoys a tropical climate with distinct wet and dry seasons. The wet season spans from March/April to October and dry season from November to February/March. Abeokuta experiences August break in the west wet season (Omotosho, 1988). The mean annual temperature is 27^0 C while the mean relative humidity ranges from 42% in February to 77% in July (Adejuwon and Adeniyi, 2011). Abeokuta area is underlain by basement rocks which are predominantly migmatites, biotite-granite gneiss, porphyritic granites, with minor pegmatites and quartz vein (Elueze and Bolarinwa, 200l1). Overlaying the basement rocks are Cretaceous sedimentary sequence comprising the Abeokuta Formation composed essentially of lithology which vary from basal conglomerate through sand clay-shale faces. It is on a huge expanse of crystalline granite rock to an extent that an area of the basement rock complex covering about 1,200 square miles was mapped during the survey of the Western Railway (Wilson, 1922).

The rock, granodioritic gneiss that does not make an ideal aggregate as it is somewhat strongly foliated, contains some pegmatite materials and the biotite contents. The gneiss pegmatite granite rocks contain relatively high concentrations of uranium, thorium and their decay products (Cothern and Lappenbusch, 1983; Ademola and Farai, 2006). In addition granite rock is known to contain high distribution of potassium up to about 3.5% (NCRP, 1991; Akhter et al., 2003). The granite rock in Abeokuta which is the nearest crystalline rock to Lagos and the southwestern Nigeria continued to provide large quantities of broken stone for construction works to this region. Due to the large mass area of the granite rock, quarries are found in many villages and towns near Abeokuta. In fact, the history of the first quarry in Abeokuta was dated back to 1904 when Aro Quarry, the largest stone quarry in Nigeria, was sited to supply large blocks of rock for the Lagos habour mole (MMP, 1964).

1.5 Justification for the present study

The exploration and exploitation of natural resources for the purpose of economic and social development may result in the enhancement of the natural radioactivity levels in

the environment. The natural radioactivity levels in the soils of some locations in Jos and Abeokuta were reported to be significantly higher than the world average (Farai and Jibiri, 2000b). The radioactivity levels in food crops grown in such soils may also increase through the plant root uptake. It is therefore necessary to measure the radioactivity levels in the food crops grown and consumed by the population in the study areas so as to ensure that food safety and consumer protection are not compromised.

1.6 Aim and Objectives of the present study

The objective of this study was to determine the levels of ^{40}K, ^{226}Ra and ^{232}Th in the food crops and farm soils and the associated cancer risks among the population in the areas. The aims of the study are as follows:

(i) determine the activity concentrations of naturally occurring radionuclides (^{40}K, ^{226}Ra and ^{232}Th) in various agricultural produce from the two high background radiation areas of study.

(ii) determine the activity concentrations of these radionuclides in soil samples from some of the farm lands.

(iii) estimate the effective dose due to the ingestion of the crops grown in these areas.

(iv) determine the external absorbed dose rate due to the radioactivity of the soils in the farm lands.

(v) evaluate the cancer risks due to the radiation exposure of the populations in the two areas.

CHAPTER TWO
LITERATURE REVIEW

2.1 Food Radioactivity Pathway to Man

The rate and level of absorption of radioactive elements from soil by plants depends on factors such as the soil type, climate conditions, plant type, and chemical form of the elements. Other factors are time of deposition relative to plant growth cycle and distribution of activity within the soil (Boone et al., 1981). The time of deposition of the radionuclides is likely to have an appreciable effect on root uptake rate, especially during the early period of the plant. The natural radionuclides in the soil enter the food crop through the plant-root uptake and are transferred to the edible parts of the crops via plant roots (Pantelica and Salagean, 1997). In general, the retained radionuclides in soil pass into the root system in the same manner as non-radioactive elements enter the plant roots. In addition, there can be direct deposition on above ground parts with subsequent translocation to the edible parts of the food crops. The processes of radionuclides entrance into food crops include direct deposition on to the leaves or exposed parts of the plants that are eaten by human being or other animals; persistent in soil layers from where they are taken up into growing plants through the roots; re-suspension as dust from the soil or any other exposed surfaces and being washed from the surface or deeper ground layers into water sources that are used for irrigation. The radionuclides enter human body system through ingestion of foodstuffs. In view of the potentially dangerous effects of radioactive isotopes contained in foods, no effort should be spared in their quantitative determination in all the identifiable pathways. Figure 2.1 shows pathways of radionuclide to man as it is always important that dose assessments should include all relevant pathways specific to issue under consideration (Camplin et al., 2002). The estimated amounts of each radionuclide that are absorbed from the gut and retained in the body organs can be determined if the concentration of different radionuclides in each article of diet is measured and the consumption rates of the foodstuffs by population are known. In other words, the level of radiation dose to man depends on the quantity of food consumed and the concentrations of the radionuclides in such foodstuffs.

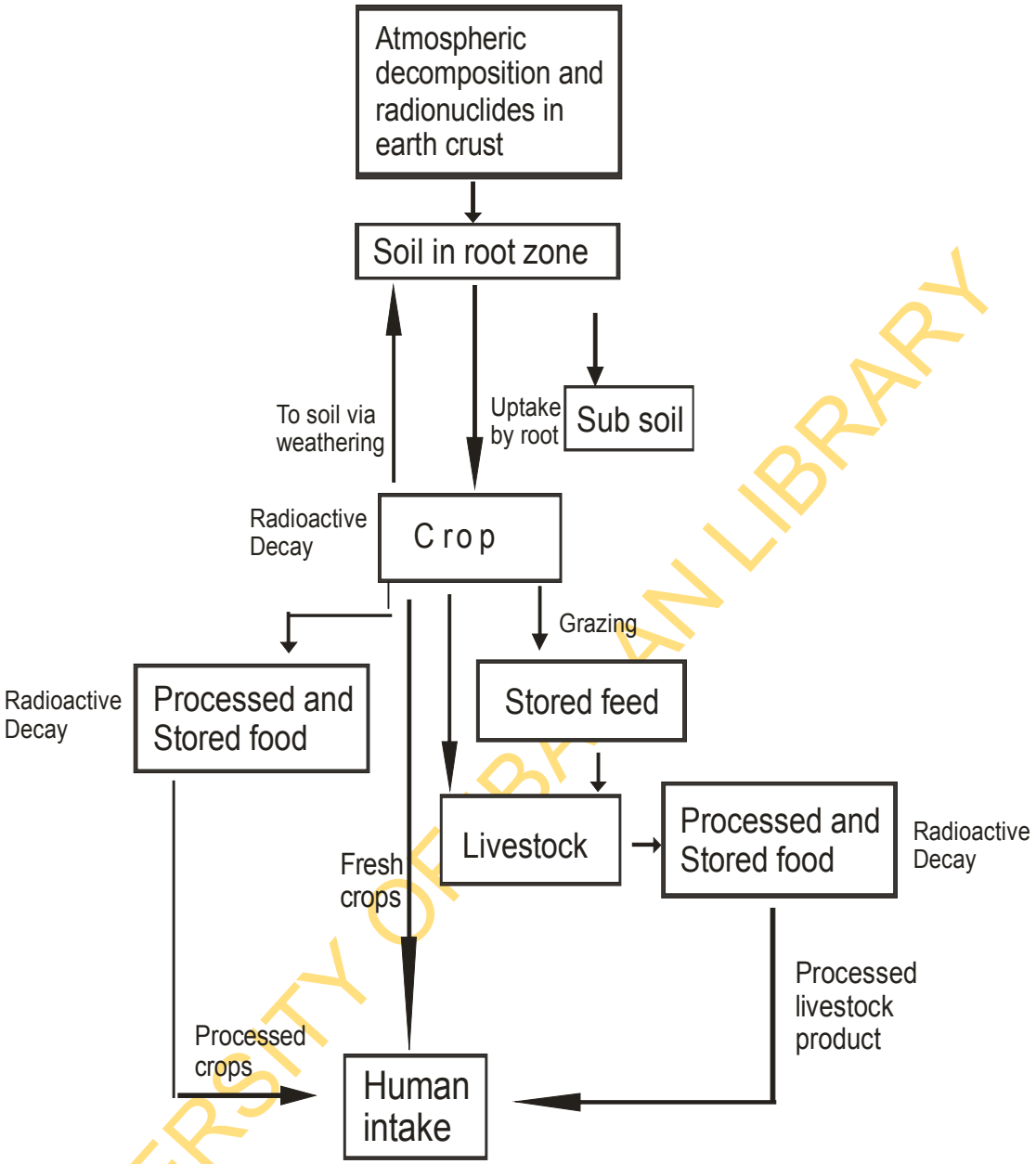


Fig. 2.1.: Pathways of radionuclide to man (After Boone *et al.*, 1981).

2.2 Food Nutrients

The first requirement of any human population for survival is food. Food is any liquid or solid material which when eaten and digested provides the body with nourishment. Food contains different nutrients that perform different functions in the body. Among the functions

are, provision of heat and energy to the body; protection of the body from diseases; and helping in the growth and repair of the body tissues. The human body is like a machine that needs fuel, good maintenance and regular repair. These needs are met by eating food. Food is needed in form of carbohydrate, fat and oil for energy and heat; protein for body-building; minerals and vitamins for body protection and proper functioning of the body. Food nutrients are simple chemical substances that are contained in food. The six food nutrients are carbohydrates, proteins, fats and oils, minerals, vitamins and water. The sources of carbohydrates are yam, cassava, maize, wheat, potatoes. All the carbohydrates provide the body with heat and energy for work. Any excess carbohydrates in the body are stored as body fats. The sources of fats and oils are groundnuts, palm oil and margarine. They provide the body with heat and energy and the excess are stored as body fats. The sources of proteins are soya bean, beans, meat, fish, eggs, and milk. They provide growth and build new tissues as well as repair worn out or damaged tissues in the body. The sources of minerals are green vegetables, beans seafood and milk. They support the growth of bones and teeth, and proper functioning of the body. The sources of water are fruits, vegetables, beverages and drinking water. Water aids digestion and it is important for body tissues and fluids such as saliva, blood, urine and sweat. Human growth metabolism depends on a balanced diet that consists of certain fractions of carbohydrates, protein, fats and oil, and water. The supply of optimum quantities of inorganic micronutrients is a necessity for the growth. These micronutrients constitute a small fraction of the whole diet but play important role in various metabolic processes. Their excess or deficiency may affect the normal biochemical functions of the body. The natural radioactivity from the ^{40}K radionuclide which is a constant fraction (0.0118%) of potassium varies significantly in different foods. The radioactivity from ^{40}K alone is typically 50 Bq/kg in milk, 165 Bq/kg in potatoes and 125Bq/kg in beef (IAEA, 2002). Potassium is very significant and plays an important role in cellular and electrical functions as it is a predominant positive electrolyte found in human body cells. It regulates transfer of food nutrients to the body cells, builds the body muscles and aids normal growth. The presence of uranium in food and water subjects man to daily intake between 1

to 18 micrograms (Taylor and Taylor, 1997). Uranium ingested by man is absorbed from intestine, into the blood stream, and is rapidly deposited in the tissues, predominantly kidney and bone. In the blood stream, uranium reacts with red cells and rapidly destroys them. Renal toxicity is a major adverse effect of uranium, other effects are observed on the cardiovascular system, liver, muscle and nervous system. Ingestion of thorium is associated with health hazard. Studies have shown that inhaling thorium dust causes an increase risk of developing lung cancer, bone cancer and cancer of the pancreas (Taylor and Taylor, 1997)

2.3 Food Crops Grown in Nigeria

Nigeria enjoys warm tropical climate with relatively warm temperatures throughout the year or two seasons. The rainy season lasts from mid-March to November in the south and from May to October in the north; and the dry season which occupies the rest of the year (Oyenuga, 1967). Most parts of the country experience rich soil and good rainfall that encourage good production of food crops. The types of food crops grown in Nigeria are grouped into cereal, roots tubers, vegetables, legume and spices (Maziya et al., 2004). Cereals and tubers that constitute the most important food basket in Nigeria (Arogunjo et al., 2004) are grown in almost all the part of the country. A large percentage of the total diet for both medium and low income consumers is hinged on cereals and tubers. The food crops grown in different parts of Nigeria are discussed below:

(i) Cereals including maize, millet, Guinea corn and rice are largely produced in many states like Benue, Kogi, Enugu, Anambra, Imo, Abia, Jos-Plateau, and Ogun in Nigeria.

(ii) Tubers including yam, cassava and potatoes are produced in some states of the country like Benue, Kogi, Anambra, Imo, Ogun, Delta and Edo.

(iii) Pulses including cowpea, groundnuts, soya beans, different variety of beans are largely produced in the northern parts of the country.

(iv) Vegetables including tomatoes, okra, spinach, bitter leaf, water leaf and onion are grown in almost all part of the country but onions are grown in large quantity in the north.

(v) Fruits including citrus fruits, like sweet orange, tangerine, and lemon, mango, pineapple and cashew are grown in different part of the country.

When food crops are grown on soils which contain radioactive elements, the crops absorb these radioactive elements along with other nutrients and through plant root uptake.

When the food crops are consumed, the radionuclides further enter human thereby causing internal radiation exposure.

2.4 Radioactivity Measurements in Food Crops.

Natural radioactivity originates from radionuclides found in the earth crust. Majority of the radionuclides are present as decay of ^{232}Th and ^{238}U, distributed by natural geological and geochemical processes, in addition to non series naturally occurring radionuclides such as ^{40}K radionuclide (Olomo, 1990; Mlwilo et al., 2007). The realization of the presence of radionuclides in food crop with its health implications has prompted some authors to carry out radioactivity measurements in different food crops across the world. Pantelica and Salagean (1997) reported that the radionuclides in soils enter food crops through plant-root uptake. It has also been reported that about one-eighth of the mean annual effective dose due to natural sources is caused by intake of foods (UNSCEAR, 2000; Hernandez et al., 2004).

The presence of natural radionuclides in food crops has raised concerns and worries among scientists worldwide. This concern prompted different authors (Takagi et al., 1994; Hashimoto and Tanabe, 1997; Min-Seok, 2008; Akhter et al., 2003) to investigate radioactivity levels in various food items. In Nigeria, the presence of radioactivity in the environment posed anxiety of possible retention of the radionuclides in food crops. Following this fear of elevated levels of radionuclides in food crops, Olomo (1990) carried out measurements of the natural radioactivity in some Nigeria foodstuffs including cereals and tubers. The measurements showed that the activity concentrations of ^{40}K, ^{238}U and ^{232}Th were significantly low. Other studies in the Nigerian environment include Arogunjo (2003) that investigated the natural radionuclide contents of some local cereals in Akure; Eyebiokin et al., (2005) that determined the activity concentrations in Ugwu (Telfairia Occidentalis) vegetables from Ondo State; Arogunjo et al., (2005) that determined the levels of natural radionuclides in some Nigerian cereals and tubers.

The economic and social needs in exploiting natural resources have prompted some countries in the world to embark on industrial mining and milling activities. The uncontrolled mining and milling activities have led to a number of environmental problems including land degradation, soil erosion, deformation and alteration of surface drainage. Besides the waste products resulting from the activities may modify the radioactivity levels in the soils that are used for agricultural purposes. As a result, the radioactivity levels in the foods grown on such soils may be augmented through the plant-

root uptake. The great interest expressed worldwide over the naturally occurring background radiation in foodstuffs from mining environments led to the performance of extensive work by some authors (Mc Donald et al., 1999; Mlwilo et al., 2007; Jibiri and Agomuo, 2007; Arogunjo et al., 2009). For instance, Jibiri and Agomuo (2007) carried out radioactivity measurements in some staple food crops, including cassava, maize, Guinea corn and potatoes collected directly from farmlands in Jos where series of mining had taken place, while Arogunjo et al., (2009) determined the uranium and thorium in soils, mineral sands water and food samples collected from Jos.

Application of fertilizers on the agricultural farm is one of the sources of technologically enhanced natural radiation which contributes greatly to radioactivity levels in the soils (Schmidt, 1993). The most common radionuclides in fertilizers and soils are ^{40}K, ^{226}Ra, and ^{232}Th. The levels of enhancement of radioactivity due to applied fertilizers in agricultural farms depend on the type and frequencies of application. Phosphate fertilizers are known to contain relatively high levels of uranium while potassium fertilizers are very rich in elemental potassium that contains about 0.0118% as ^{40}K. The anxiety over radiological enhancement and possible elevated radioactivity in food crops grown on farm lands where fertilizers are applied have been investigated (Mortevedt 1992; Bolca et al., 2007). The elevations of radioactivity levels due to application of fertilizers on the farms where food samples were collected and analyzed by the authors were found to be insignificant.

Some areas on the globe including Guarapari in Brazil, Yangjian in China, Ramsar in Iran, Kerala and Tamil Nadu areas in India are known with high background radiation while the high radioactivity scenario in Nigeria has been documented (Jibiri, 2001) . The population growth and movement, industrial development and food security have resulted into pressure to use agricultural lands that contain relatively high radioactivity level. The realization of high background radiation levels and the fear of enhanced radioactivity levels in food crops grown in these areas necessitated measurements of radioactivity in different foodstuffs by some authors (Mistry et al., 1970; Avadhani et al., 2001; Samavat et al., 2006; Shanthi et al., 2009). The radionuclide contents in the food crops analyzed were very low including those from high background radiation areas.

The application of ionizing radiation in research for energy development results in the possible release of radionuclides into the environment if not properly handled. In Nigeria, two research centers established for purpose of research training and developments are creating fears of possible leakage of ionizing radiation into the

environment. The fear of elevated radioactivity in the environment of Obafemi Awolowo University where a Tandem linear accelerator is operational at the Center for Energy Research and Development, prompted Akinloye and Olomo (2000) to determine the natural radioactivity in some tubers cultivated in farmlands within Obafemi Awolowo University, Ile-Ife. Akinloye et al., (1999) determined the meat and poultry consumption contribution to the natural radionuclide intake of the inhabitants of Obafemi Awolowo University, Ile-Ife, Nigeria. The radioactivity levels in both meat and poultry products were low despite the fact that the samples used for the measurements were collected from the site where a nuclear accelerator is operational.

The use of ionizing radiation in development of nuclear technology and the associated nuclear leakages or accidents and nuclear weapon tests, have led to the radioactive contamination of soils and foods in various countries of the world. A variety of radionuclides of artificial radioactivity results mainly from nuclear weapon testing, major nuclear power accidents and illicit disposal of radioactive wastes. The Chernobyl nuclear reactor fire disaster on 26 April, 1986 has motivated the needs to develop monitoring techniques for radioactive contaminations in the environment particularly in foodstuffs. After the Chernobyl, the accumulation of ^{137}Cs mostly in mushrooms was reported in Europe (Haselwandter et al., 1988). This report was motivated by the fear of possible elevation of radionuclides in various other food crops in different parts of the world. As a result, the foodstuff intervention levels were set by the European Community (EC) which was adopted in many countries including USSR (Willen and Teunis, 1992). The EC set the maximum permissible radiocaesium levels applicable to imported milk and baby food as 370Bq/kg and 600Bq/kg for all other food items. The realization of release of radiocaesium into the environment after the Chernobyl reactor accident and awareness of the maximum dose level in foods prompted various authors (Copper et al., 1992; Shiraishi et al., 1999; Yu and Mao, 1999; Gaso et al., 2000; Badran et al., 2003; and Ban-nai et al., 2004) to investigate the radioactivity in different food crops in different parts of the world. For instance Yu and Gao (1999) determined the concentration level of ^{137}Cs in potatoes from Hong Kong; Shiraishi et al., (1999) investigated stable and radiocaesium on dietary intakes in Japan; Gaso et al., (2000) determined ^{137}Cs element in edible mushroom from Mexico and Badran et al., (2003) investigated the levels of ^{137}Cs and ^{40}K in edible parts of some vegetables consumed in Egypt. The activity concentrations in all the food analyzed were low.

In Nigeria the fear of possible elevated radioactivity in foods had led to the investigation of internal radiation dose as a component of radiation health burden. Few months after Chernobyl reactor accident, a pioneering work on the measurements of activity concentrations of ^{137}Cs in imported milk from European countries was carried out by Farai (1993). The work reported activity concentration of ^{137}Cs ranging from 0.5 to 5.1Bq/kg in eleven widely consumed imported milk products from countries in Europe. Similar radioactivity measurement was carried out for milk products imported into and consumed in Nigeria ten years after Chernobyl nuclear power-plant accident (Osibote et al., 1999). No artificial radionuclide was detected in the milk products. About twenty years being two-third of the ^{137}Cs half-life (32.2 yrs.) after the Chernobyl nuclear reactor accident that led to the release of radioisotopes into the environment, Jibiri and Okusanya (2008) carried out measurements of radionuclide contents in food products from domestic and imported sources in Nigeria with the aim at ascertaining the radionuclide contents still present in imported food products from some European countries which were once contaminated with the radioactive fallouts from the accident. There was no detection of ^{137}Cs or any other artificial radionuclides in the imported food imported.

Abeokuta and Jos cities have been reported to be much elevated natural background radiation areas. The reported dose rate values in both areas are four times higher in magnitude than the world average (Farai and Jibiri, 2000b). The population growth and movement, industrial development as well as need for food security have resulted in the use of all available agricultural lands including those containing high level of radioactivity in the study areas. Radionuclides entre food crops grown on such farmlands through plant-root uptake thereby expose consumers to internal radiation exposure. The concern of United Nation for sustainable food security is to ensure access to sufficient, nutritionally adequate and safe food for all people. In addition the International Atomic Energy Agency (IAEA) and Food and Agriculture Organization (FAO) always advocate for plant, animal and consumer protection at all times. However the realization of elevated radiation levels in these cities necessitated various studies and measurements of radioactivity in different environmental matrices (Sanni, 1977; Babalola, 1984; Sanni et al., 1985; Oresegun and Babalola, 1990 and 1993; Farai and Jibiri, 2000b; Farai and Ademola, 2001; Farai and Vincent, 2006; Ademola and Farai, 2006; Jibiri and Agomuo, 2007 and Ademola, 2008b). Despite the volume of work in the cities and other cities in Nigeria, only very few studies involved measurements of natural radioactivity foodstuffs. Some of the reports include: Radioactivity in some Nigerian foodstuff (Olomo,1990); Activity concentration and

absorbed dose equivalent of commonly consumed vegetables in Ondo State Nigeria (Eyebiokin et al., 2005) and Trace elements and radioactivity measurements in some terrestrial food crops in Jos-Plateau, north central, Nigeria (Jibiri and Agomuo, 2007). Scientific data is still sparse on the radionuclide contents of food crops and their radiological implication on the population in Jos and Abeokuta despite the high radioactivity levels in the two areas. It has been noted that ingestion of radionuclides accounts for major internal exposure of the human to radiation (McDonald et al., 1999; Fernandez et al., 2004; Hernandez et al., 2004). Therefore it is important to investigate the levels of radiation exposure from consumption of the foodstuffs from these two areas of high background radiation, which have drawn less attention from previous works.

2.5 Radiation detection and Gamma-ray spectroscopy

2.5.1 Introduction

The environment contains various degrees of radionuclides that decay and emit charged particles such as α- and β- radiations and neutral particle like γ- radiations. Measurement of radioactivity in the environment is centered on the detection of the emissions of charged and neutral particles from the decaying radionuclides. The emitted particles are easily observed when they interact with matter through the excitation and ionization effects they cause in the matter. The methods in which these effects are used for radiation detection depend on the mode of interaction, type and energy of radiation.

However in the energy region of 0.01 and 10.0MeV which is usually encountered in an ordinary environment is the energy range for interaction of γ- and x-rays with matter. Their interaction of the particles may be explained well by the three different modes of interactions: photoelectric, Compton and pair production interactions.

2.5.1.1 Photoelectric Effect

Photoelectric effect is the process of ejection of electrons from an atom after the absorption of light photon. In Photoelectric effect interaction, an incident γ- or x-ray photon collides with an atomic electron in the absorbing material, and transfers all of its energy to the electron. If the energy is sufficient to release the electron from its atomic orbital shell, the atom is ionized. The photoelectron has a net kinetic energy equal to the total energy of the photon less its atomic binding energy. The energy of the photoelectron, E_e is given as:

$$E_e = E_\gamma - E_B \qquad (2.1)$$

where E_B is the binding energy of the electron to the atom and E_γ is the incident photon energy. Photoelectron production occurs only when the energy of the incident photon, E_γ is equal to or greater than the binding energy of the electrons in the absorbing materials. A vacancy is created mostly from the tightly bound shell (e.g. K-shell) due to the production of photoelectrons. This is promptly filled by electrons from the higher shells leading to the production of characteristic x-rays. According to James (1995) and Tait (1980), the cross-section for photoelectric effect can be written as:

$$\sigma_{p.e}=\delta E_\gamma^{\ 7/2}\rho Z^5 \qquad (2.2)$$

where δ = a constant,

Z = the atomic number of the absorbing material,

ρ = the density of the absorbing material.

Equation 2.2 shows that photoelectric effect predominates, for most materials, at low photon energies (<0.1 MeV) and that photons are absorbed much more strongly in high Z materials.

There light output in scintillation spectroscopy due to photoelectric effect is large because the total energy of the incident photon is absorbed to excite the crystal.

2.5.1.2 Compton Effect

This is the second method by which γ- and x-ray photons interact with matter. In Compton Effect, the photon undergoes elastic scattering with a free or loosely bound electron in the outermost atomic shell. The photon energy reduces from hν to hν′ after transferring part of its energy to the electron. Thus its frequency is changed and its wavelength increased from λ toλ′. The remaining part of the original photon's energy is radiated as a lower-energy photon in a direction different from the one creating it. The electron is also scattered at a different angle and its energy is hν - hν′. The energy hν - hν′ that is deposited in the material in the interaction can be calculated by applying the conservation laws for energy and momentum. The change in wavelength of the photon as expressed in Birks (1964) and Tait (1980) is given by:

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_0 c}\left[1-\cos\theta\right] \qquad (2.3)$$

where $\Delta\lambda$ is the wavelength shift, λ' is the scattered photon wavelength, λ is the incident photon wavelength, m_o is the rest mass of electron, h is the Plank's constant and θ is the angle of scatter of photon.

The energy of the scattered gamma ray, E'_γ in terms of the scattering angle θ is given by:

$$E'_\gamma = \frac{E_\gamma}{1+\left[\frac{E_\gamma}{m_0c^2}\right](1-\cos\theta)} \tag{2.4}$$

And for the kinetic energy of the electron $E_{k.e}$ as:

$$E_{k.e} = E_\gamma - E'_\gamma \tag{2.5}$$

This can be shown as:

$$E_{k.e} = \frac{\left(\frac{E_\gamma^2}{m_0c^2}\right)[1-\cos\theta]}{1+\left(\frac{E_\gamma}{m_0c^2}\right)[1-\cos\theta]} \tag{2.6}$$

where m_o is rest mass and m_oc^2 is the rest energy of the electron. From equation 2.6, the minimum value of $E_{k.e}$ is zero when $\theta = 0^0$. And the maximum value referred to as Compton edge, E_c corresponds to a head-on collision in which the photon is scattered backwards, is when $\theta = 180^0$.

This maximum energy value is obtained as:

$$E_c = E_\gamma\left[\frac{2E_\gamma}{m_0c^2+2E_\gamma}\right] \tag{2.7}$$

The energy loss in Compton Effect predominantly range from 0.6 and 2.5 MeV is quite large and forms a continuous distribution of pulse heights termed Compton plateau in gamma spectroscopy. Compton plateau of higher energies always form the background of the photopeaks of lower energies and thereby poses a problem to an accurate evaluation of the net area due to photoelectric absorption in γ-spectrometry. The problem was taken care of in the present work by measuring the background count of the detector and deducting it from the total count to obtain the net count in each measurement.

2.5.1.3 Pair Production

In pair production, gamma ray with sufficient energy is totally absorbed in the nucleus of the absorbing material and replaced by an electron-positron pair produced in its place. The energy equation of the process is given by:

$$h\nu = E_e + E_p + 2m_oc^2 \quad (2.8)$$

where E_e and E_p are the kinetic energies of the emitted electron and positron respectively. Equation 2.8 implies that pair production can take place above photon energy $2m_oc^2$ (1.02 MeV). Because of the unstable nature of positron particle produced, it interacts and annihilates with an electron almost immediately when its kinetic energy becomes zero, to form two photons with energy 0.511 MeV each in opposite direction. This usually leads to a photo peak at 0.511 MeV which can easily be confused with the gamma peaks of the source being measured especially if the source has gamma energy close to 0.511 MeV. A photopeak at 0.511MeV is therefore not usually suitable for the activity measurement of a source.

Unlike the other two photon interactions, pair production has a cross-section σ_{pp} which increases, although slowly, with photon energy E_γ and the interaction tends to be dominant at high energies.

The cross-section can be written as:

$$\sigma_{p.p} = cZ^2\rho \ln E_\gamma \quad (2.9)$$

where c is a constant.

The net effect of the above three interactions is an exponential attenuation in the intensity of a beam of gamma rays passing through a thickness x of an absorbing material. This is described by the equation:

$$I = I_0 e^{-\sigma x} \quad (2.10)$$

where I_0 is the initial intensity at x = 0

σ = the linear absorption co-efficient due to all the effects.

2.6 Principle of Scintillation Spectroscopy

A scintillation detector is a transducer that changes the kinetic energy of an ionizing radiation into a flash of light. Several organic and inorganic compounds exhibit this phenomenon though there are differences in their scintillation processes. Sodium iodide activated with thallium, (NaI (Tl)) is an inorganic crystal. It is the commonest scintillator detector and has a unique suitability in γ-ray measurements because of its high

efficiency for γ-rays. NaI(Tl) crystal is highly hygroscopic so it is usually enclosed in an air tight and a light proof covering. The covering is typically a light metal like aluminum (Al) that is thin enough to allow γ-radiation to pass through without significance attenuation. The cylindrical detector is free at one face while the other has a window through which it is couple to a photomultiplier (PM) tube which detects the small visible light photons produced in the crystal and converts them into amplified electrical pulses which can be fed into suitable analyzer systems. The scintillation detector used in the measurements of activity concentrations of radionuclides in the present work was a Canberra 76 mm x 76 mm NaI (Tl) crystal detector. A schematic diagram of a typical scintillation detector which is coupled to the photomultiplier tube is shown in Fig 2.2.

2.6.1 Principle of radiation detection by NaI (Tl) crystal

When a gamma photon incident on the scintillator crystal, it dissipates its energy E completely in the scintillator and N number of photons are produced. The number of photon produced is given by:

$$N=\frac{Eq}{\omega_0} \qquad (2.11)$$

where q is the luminescence quantum efficiency, which is the probability of a photoelectric interaction of the incident photon and ω_o is the average energy of a single photon which is about 3.0 eV for NaI(Tl). These N photons impinge on the photocathode of the photomultiplier tube and are converted into photoelectrons, which are directed to incident on the first dynode of the photomultiplier tube. The total number N_c of photoelectrons at the first dynode is given by:

$$N_c = \frac{Eq}{\omega_0} mc_{p.e} g_c G \qquad (2.12)$$

where G is a fraction of incident photons called the light collector efficiency impinging on the photocathode and are converted into photoelectrons; $C_{p.e}$ is the photo-quantum efficiency of the window-cathode system; m is a factor between 0 and 1 depending on the degree of spectral matching between the scintillation spectrum and the spectral responses of the photocathode; g_c is the efficiency with which the first dynode collects the number of electrons arriving. These efficiencies are affected by a number of factors. G is determined by self-absorption, reflection loses, light trapping, optical flaws and the optical geometry of the photocathode. In NaI(Tl), G can be made nearly unity by coating the detector with

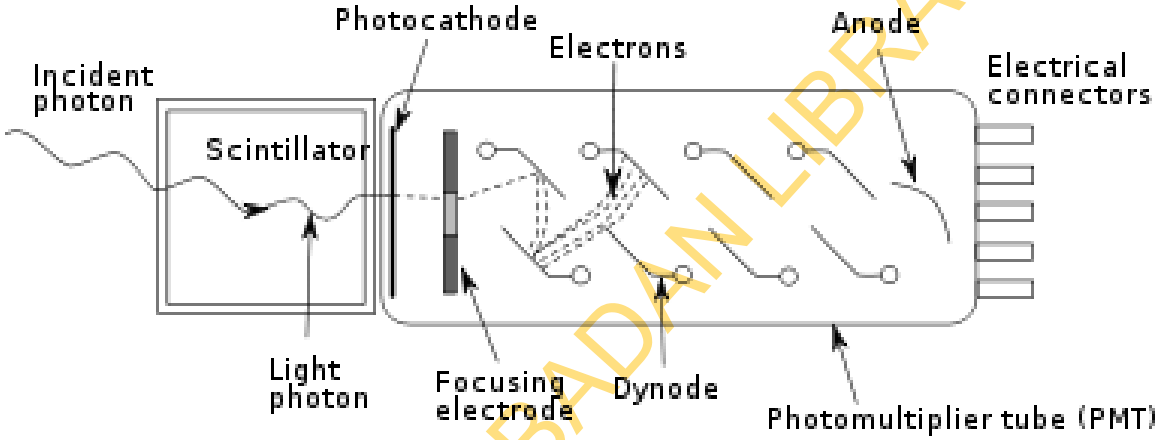


Fig 2.2: A scintillation detector couple with a photomultiplier tube (PMT) (After Wikipedia, 2012)

a reflector like MgO thereby making its self-absorption very small. The term $mC_{p.e}g_c$ depends in a complex manner, on the wavelength and the point of incident of the photons on the cathode. The photoquantum efficiency, $C_{p.e}$, depends on the thickness and the material of the cathode while g_c depends on the structure of the dynode and its potential. The total number of electrons Q at the anode is given as:

$$Q = MN_c \tag{2.13}$$

where M is the overall gain resulting from the k successive multiplications of N_c electrons at each dynode is given by:

$$M = \prod_{i}^{k} m_i \tag{2.14}$$

where m_i is the multiplication at the i^{th} dynode.

It can be observed from equations 2.13 that Q is a linear function of the energy E of the initial incident photon. Apart from the number of electrons given by equation 2.13, there are a number of electrons produced due to thermionic emission in the photomultiplier tube.

The number of electrons with thermal energy greater than the work function of photocathode which are emitted as thermionic electrons varies exponentially with temperature and it is expressed (Birks, 1964),

$$n_T = AT^2 \exp -\left(\frac{Qe}{KT}\right) \tag{2.15}$$

where T is the absolute temperature, e is the electronic charge, k is the Boltzmann constant, A and Q are characteristics of the cathode material.

2.6.2 Pulse Shaping and Height Analysis.

The number of electrons that reach the anode decays according to the equation:

$$N = Qe^{-\left[\frac{t}{T_d}\right]} \tag{2.16}$$

where T_d is the modified decay time of the scintillator which is about 0.25 μsec for NaI(Tl). This decay time constant is modified by the decay time spread effects within the PMT. The pulses may be subjected to a pile up that is a new pulse may arrive while the system is still responding to a previous pulse, thus it is important to collect information about a pulse as quickly as possible. This is usually achieved by a pulse shaping RC circuit as shown in Fig 2.3, which is normally placed after the amplifier. After shaping, the number N (t) of the electrons in the shaped output is given by Birks (1964) as:

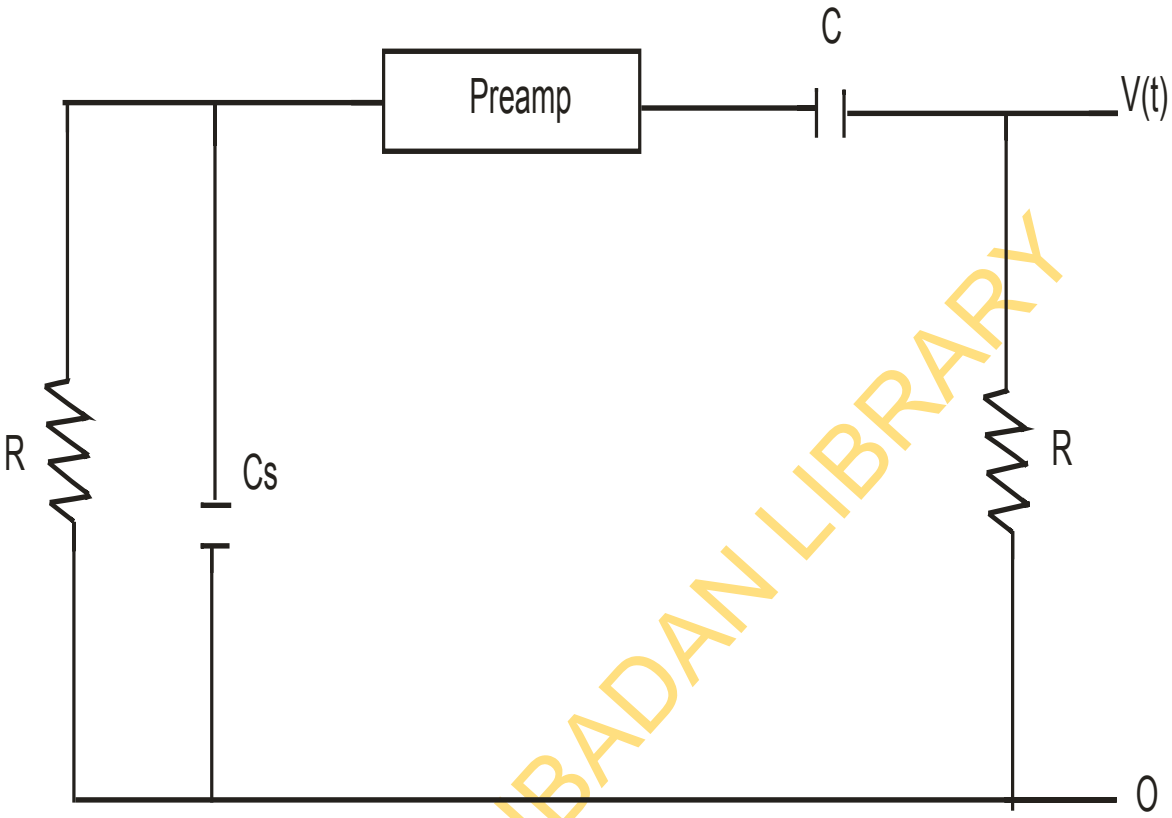


Fig 2.3: A Pulse Shaping Circuit.

$$N(t) = Q\left[\frac{RC}{RC - T_d}\right]\left(e^{-\frac{t}{RC}} - e^{-\frac{t}{T_d}}\right) \quad (2.17)$$

In gamma spectrometer application, energy spectrum is of importance. The value of voltage pulse is greater than the current pulse. Thus the voltage is given by:

$$V(t) = \frac{Qe}{C_S}\left[\frac{RC}{RC - T_d}\right]\left(e^{-\frac{t}{RC}} - e^{-\frac{t}{T_d}}\right) \quad (2.18)$$

Equation 2.17 shows that the amplitude of the pulse depends on capacitance, C, T_d and RC (time constant) of the circuit and that the pulses are of random occurrence both in amplitude and time while also revealing that the peak, V (t) of the voltage pulse is proportional to the energy dissipated by the primary radiation.

2.6.3 Pulse Selection

The pulse amplitude given in equation 2.18 is of random occurrence because of the different types of interaction in detector crystal. This is illustrated by the typical photomultiplier tube (PMT) output shown in Fig 2.4. The final spectrum is acquired by first converting the analogue information in V (t) to digital information. Then the signals with pulse amplitude less than the preset minimum energy are filtered off by using a discriminator such as Schmitt-trigger or an analogue comparator that is the signals with amplitudes less than B in Fig 2.4 are filtered and those above this level are then analyzed according to their heights. Most modern scintillation systems use multi-channel analyzer (MCA) which works on the principle of pulse-to-time conversion. The principle of pulse-to-time is illustrated in Fig 2.5; the input (I) after amplification shaping is fed into the analyzer. It is then stretched at its maximum height V (p) which is maintained constant (J). At time t_1, when the input pulse attains its maximum height, two pulses are fed in. The first (K) is a linearly increasing sweep pulse and second (L) is a series of clock pulses. When the sweep pulse reaches the height V (t) of the stretched pulse at time t_2, the timing pulses stop. The number of timing pulses in the time t_2-t_1, is proportional to pulse height V (t) and hence the energy of the radiation. The digital signal is then added as one unit into the memory word or channel which corresponds to the size of the digital information. Information about the radiation can then be obtained from the memory in the form of channel number and the number of pulses in each channel. The assessment of its intensity and other parameters thus becomes possible. This is the principle of operation of the Canberra multichannel analyzer (MCA) used in the present study.

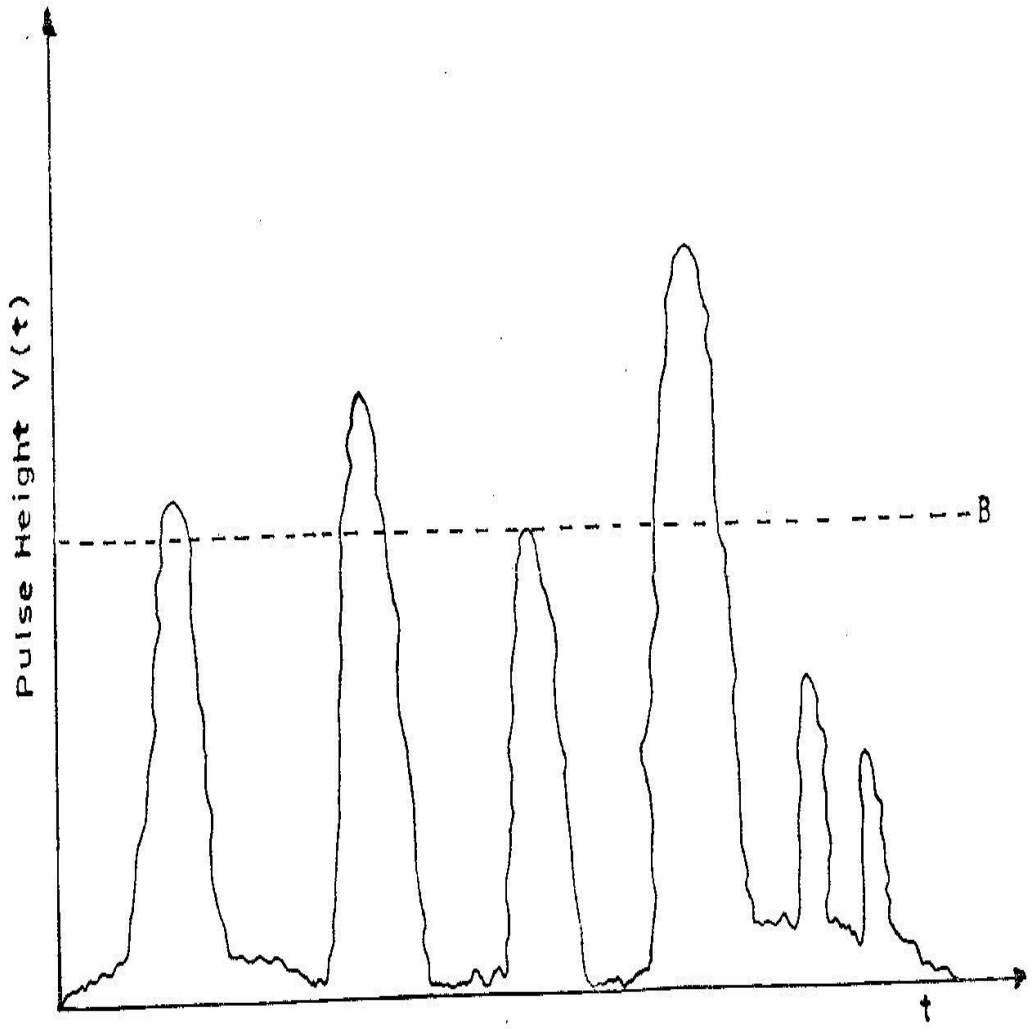


Fig.2.4: Pulse height distribution and pulse selection (Martin and Harbison, 1979)

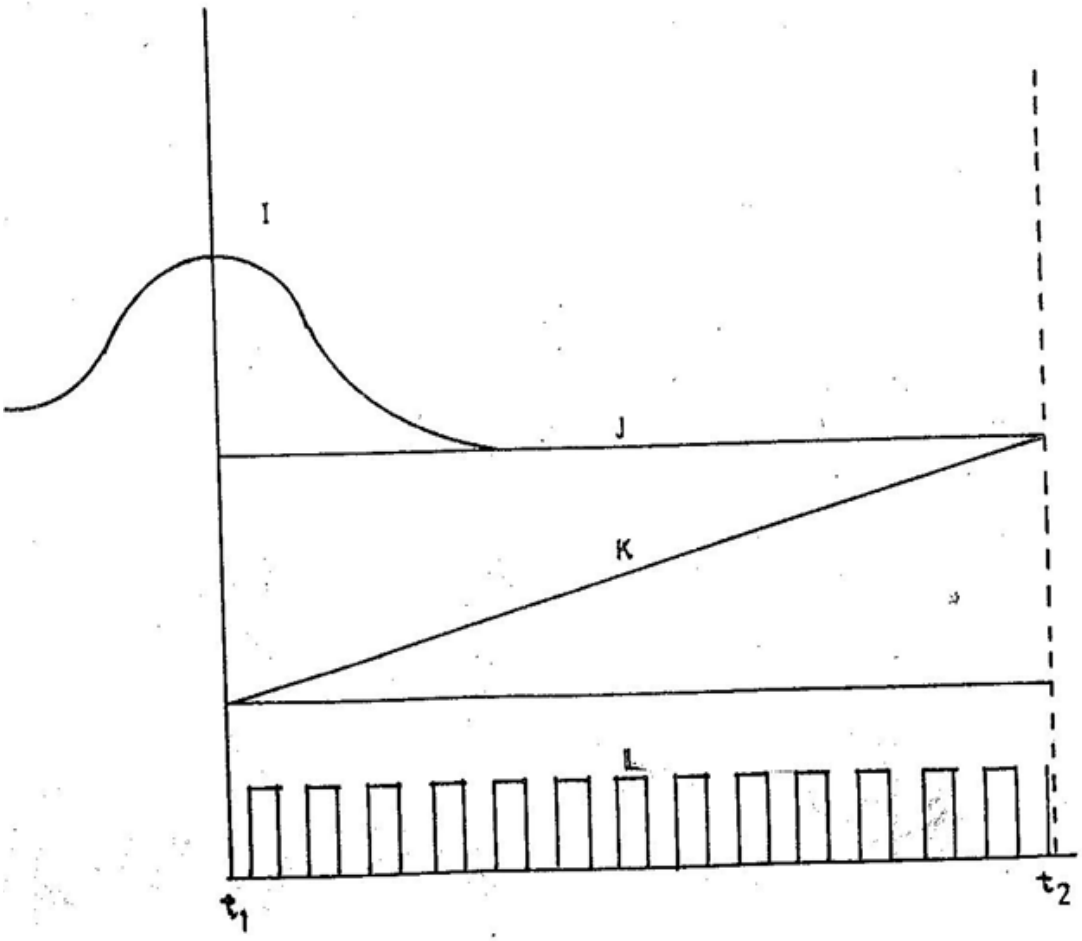


Fig 2.5: Principle of pulse height to time conversion pulse height analyzer (after Kowalski, 1970)

2.7 Gamma Ray Spectrometry

The three common processes of energy transfer by γ-rays have been discussed in section 2.5. The fast electrons, which result from these processes, provide very useful information on energy and intensity of the incident γ-rays. The system for the conversion of these fast electrons into flash of light, detected by optically matched electronic system to yield useful information concerning the primary γ-photon constitutes scintillation γ-ray spectroscopic system. The ability of the system to differentiate between radiation energies and sources is the basis of its application in this work.

2.7.1 Resolution

There is statistical fluctuation in the factors described in section 2.6 which determined the height of the pulse output from the photomultiplier tube. The result is that two pulses produced by γ-rays of the same energy may be of slightly different heights and sorted into two close channels. The photopeaks due to mono-energetic γ-rays is therefore not a single line spectrum but a distribution spread over a number of close channels. The width of this distribution is a measure of the resolution of the spectrometric system. In scintillation spectrometry, resolution R is defined quantitatively as the number of channels between the half maximum points in the photopeak ΔE, divided by the energy, E_p of the photopeak mid-point and multiplied by 100%. That is

$$R = \frac{\Delta E}{E_p} x100\% \qquad (2.19)$$

A spectrometric system with good resolution is one, which can distinguish between the photopeaks of two γ-rays with very close energies.

The reliability of the performance of any detection system has been shown by Farai (1989) to depend greatly on its resolution. The NaI(Tl) detector used in this study has a resolution of 8% and was tested for its reliability using the photopeak at 0.662MeV due to ^{137}Cs. Although this resolution is low when compared to the resolution of gamma spectrometers employing Ge (Li) and HPGe detectors, the spectroscopic system proved the capability of distinguishing the photopeaks due to the primordial radionuclides considered in this study. This is illustrated in the spectra of the radionuclides obtained by the system as shown in Fig 2.6. The combined spectra, show that ^{40}K, ^{238}U and ^{232}Th are clearly displayed at the 1.460, 1.764 (^{214}Bi) and 2.615 (^{208}Tl) MeV peaks, respectively. The evaluation of radioactivity concentrations of ^{40}K, ^{238}U and ^{232}Th carried out in this

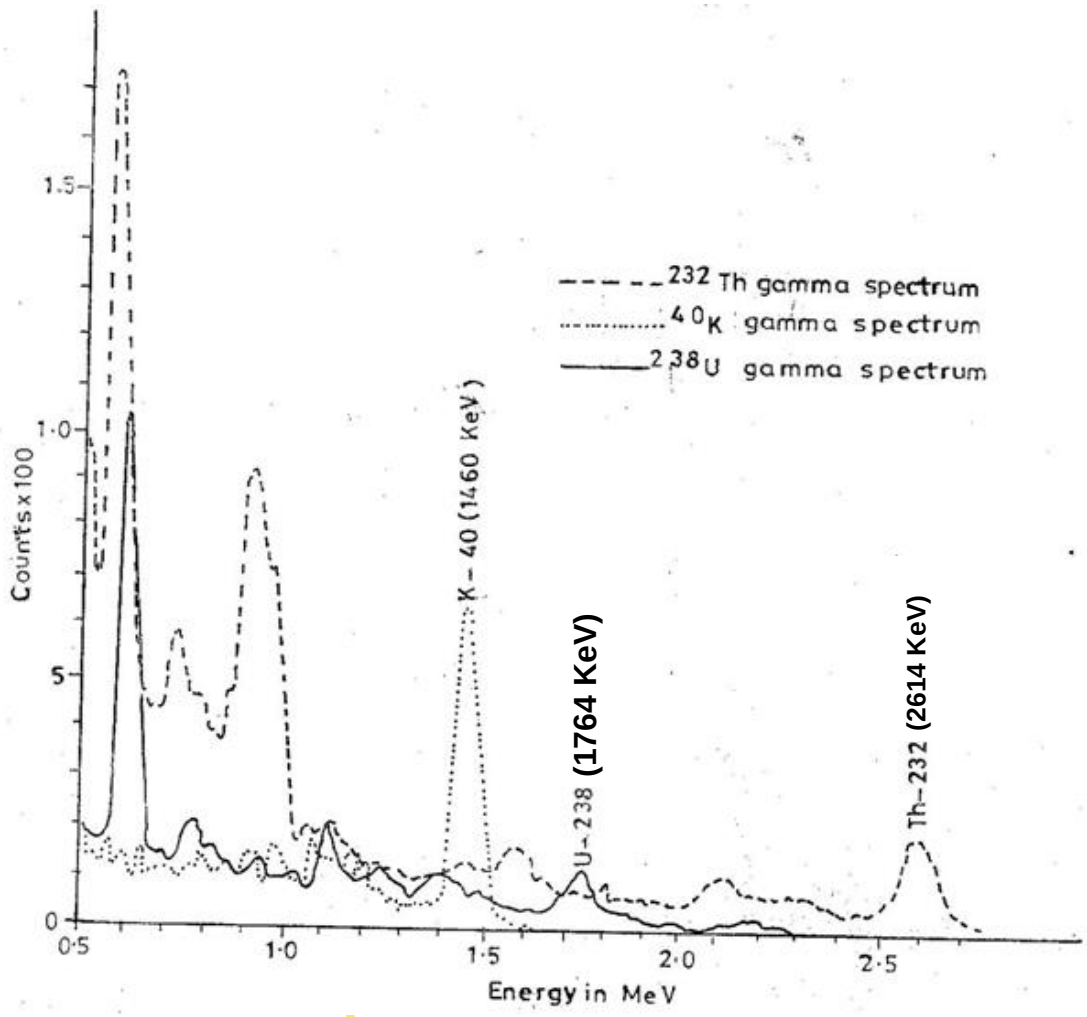


Fig 2.6: Gamma spectra of the primordial radionuclides (after Jibiri, 2000).

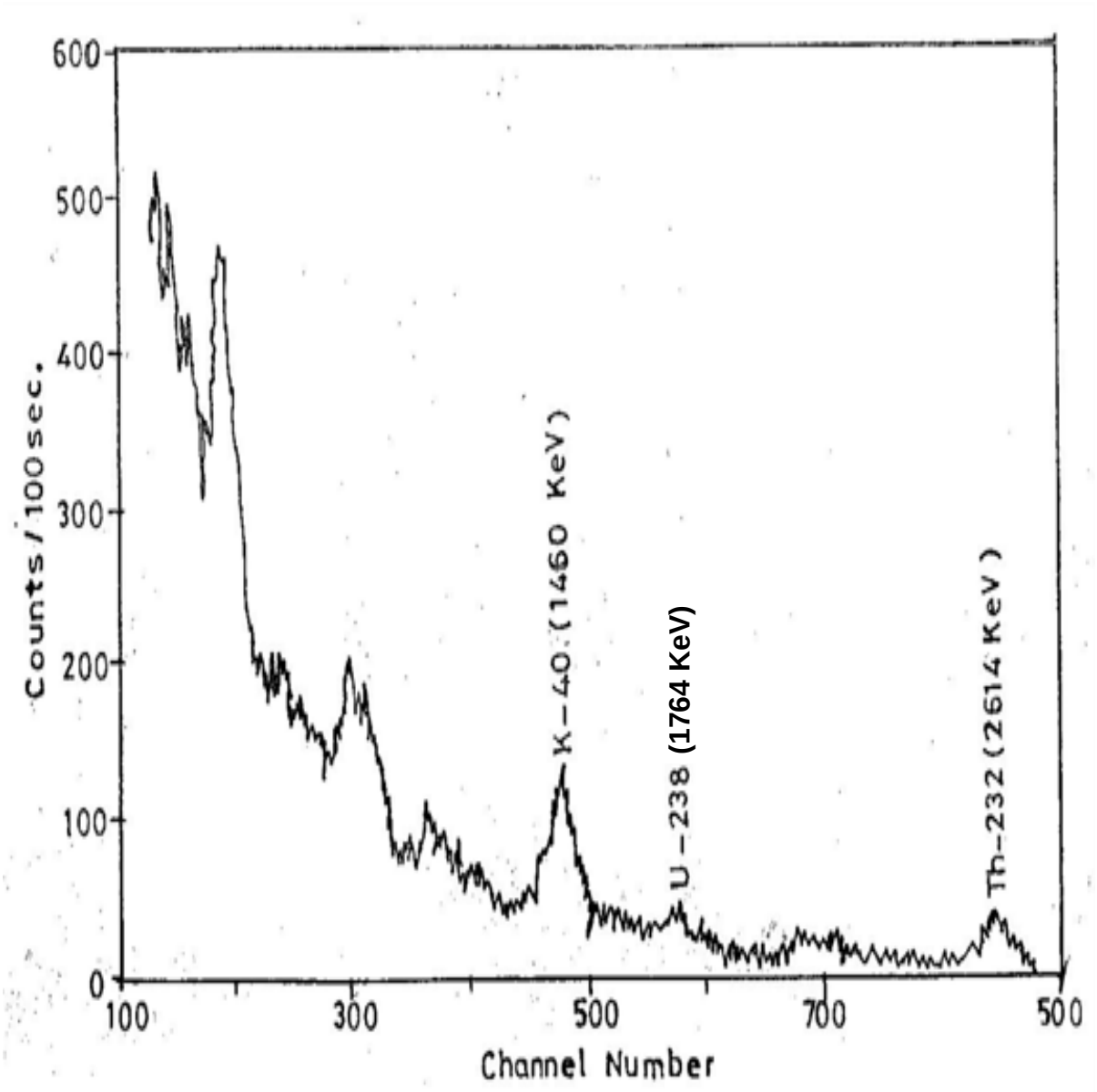


Fig 2.7: Typical spectrum of the radionuclides taken with NaI (Tl) crystal detector (After Jibiri, 2000).

work, were done using these photopeaks. This is considered good enough because of the poor resolution of NaI (Tl) detector used in the measurements. The nuclides ^{214}Bi and ^{208}Tl are members of Uranium and Thorium series with ^{220}Rn and ^{222}Rn gases causing disequilibrium between them and their parents. A typical spectrum, which is a combination of the three spectra in Fig 2.6, is shown in Fig 2.7 with the photopeaks of interest clearly displayed.

2.8 Evaluation of net area under the photopeak

It has been discussed under Compton Effect that every photopeak is associated with some amount of background counts due to other events such as electronic noise of the system, Compton plateaus of higher peaks. The actual count due to photoelectric absorption is equal to the integral count in the region of the photopeak minus the total background count in that region. The method adopted for the net area which has been programmed in the memory of the analyzer system used in this work is illustrated in Fig 2.8. A region of interest (ROI) is defined around a photopeak which is bounded symmetrically by channels d and g on either side of the photopeak. The average count $\overline{B}$ due to background events in each channel of this region has been estimated by considering three channels at the tail of the Gaussian curve on either side. This consideration of three channels is only applicable to the photopeaks of the three natural radionuclides of interest in this study, because, their photopeaks are well defined with very low continuum (Fig 2.7). For low energy peaks channels greater than 4 is usually adequate because the peaks cannot be well defined and usually will sit on a very large continuum due to the poor resolution of NaI (Tl) detector.

The average count $\overline{B}$ is given by:

$$\overline{B}=\frac{B_1+B_2}{2(3)} \tag{2.20}$$

where $B_1=\sum_{a=d}^{a=e}X_a$ and $B_2=\sum_{a=f}^{a=g}X_a$

where X_a is the content of each channel. The integral count I in the whole region is given by:

$$I = I_p + B_1 + B_2 \tag{2.21}$$

where I_p is the sum of the contents of N channels actually under the photopeak and not in B_1 and B_2.

I_p is given by:

$$I_p = \sum_{a=b}^{a=c} X_a \qquad (2.22)$$

The net area A, which is the area due to actual photoelectric absorption, is equal to the total count I_p minus the total background, $N\bar{B}$ in all the N channels.

That is:

$$A = I_p - N\bar{B} \qquad (2.23)$$

Equations 2.21 – 2.23 are stored as computation algorithm in the memory of the MCA system used in the present work. Data are processed in the memory of the MCA and the results are displayed whenever the region of interest is defined around the photo peak due to a particular γ-ray energy of a radionuclide. From equation 2.23, the accuracy of reproducing the net count, A depends on the statistical errors in the actual photoelectric events and the background events. That is, the standard deviation,σ_A, in the net count A is given as:

$$\sigma_A^2 = \sigma_P^2 + \sigma_B^2 \qquad (2.24)$$

Also, the percentage standard deviation error, E, in A is given by:

$$E = \frac{F}{A}\sigma_A x100\% \qquad (2.25)$$

Equations 2.24 and 2.25 are also stored in the memory of the MCA system to estimate error in the analysis of the samples spectra. The error statement is usually displayed along with the net count A whenever analysis is made in various regions of interest.

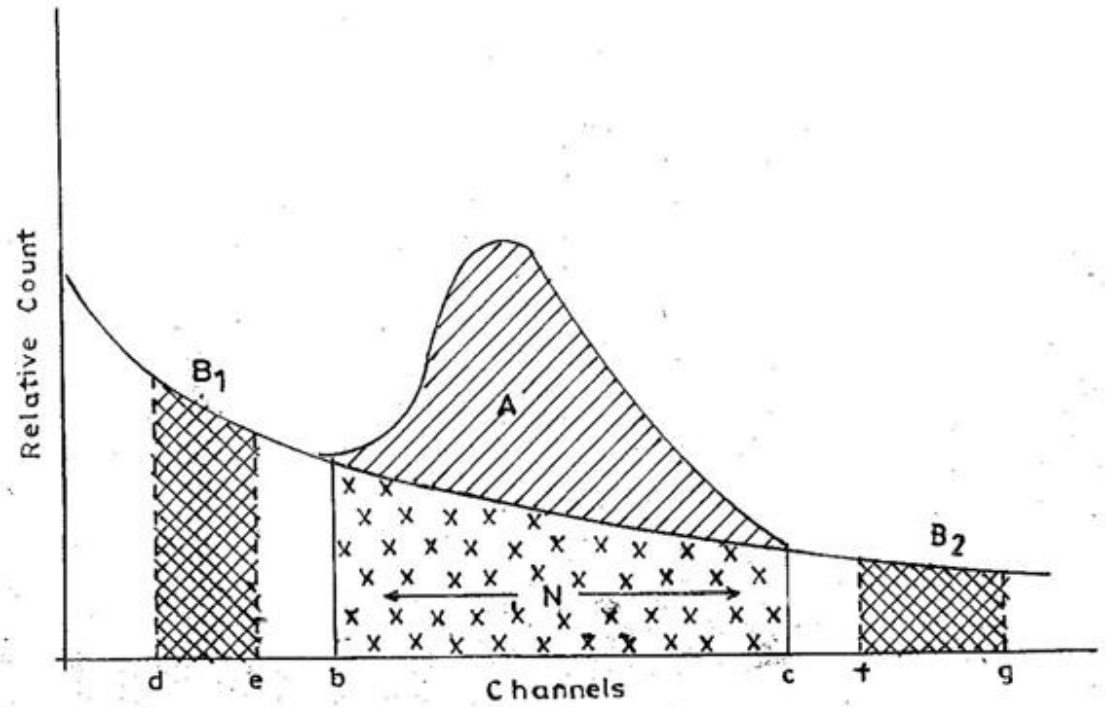


Fig 2.8: Evaluation of net area under a photopeak (After Jibiri, 2000)

CHAPTER THREE
MATERIALS AND METHODS

3.1 Calibration of the Detector

In radioactivity measurements, it is important to calibrate the detector system. This is necessary for the purpose of ensuring proper identification and quantification of radionuclides present in any assayed sample. The procedure for identifying radionuclide in any sample entails proper energy calibration while the correct quantification of radioactivity in the sample depends on proper detection efficiency calibration (Olatunde, 2004). Two types of calibrations were carried out in this work. The first was energy calibration while the second was for efficiency calibration. These calibration procedures are described below.

3.1.1 Channel- Energy Calibration

When assaying a sample, the height of gamma-spectra output obtained has direct proportionality to the gamma-energy producing the pulse. The linear response of a scintillation system with the radiation energy is fundamental to the system's good performance. The channel-energy calibration was carried out by counting the gamma-rays emitted by the standard or reference gamma source using the energy calibration (ECAL) analysis function of the MCA. The energy calibration data (Table 3.1) was fit to a linear curve shown in Figure 3.1

A linear relationship was obtained between the channel number, N and the gamma-energy, E (MeV). The relationship is given as:

$$E = 0.0117N + 0.0155 \qquad (3.1)$$

Equation 3.1 was stored in the memory of the MCA for purpose of identifying the various radionuclides that may be present in the samples through the gamma energies they emit.

3.1.2 Determination of detection efficiency of the spectrometer.

The detection efficiency of the spectrometer used in this study was determined experimentally by using standard sources. The precision of the experimental determination of the efficiency depends on many factors including the quality of the reference sources and the geometry of the detector.

Table 3.1 Energy Calibration Data

Radionuclides	Energy (MeV)	Channel
Cs-137	0.662	54
Co-60	1.173	100
Co-60	1.333	114
K-40	1.460	124
Bi-214	1.764	148
Tl-208	2.614	222

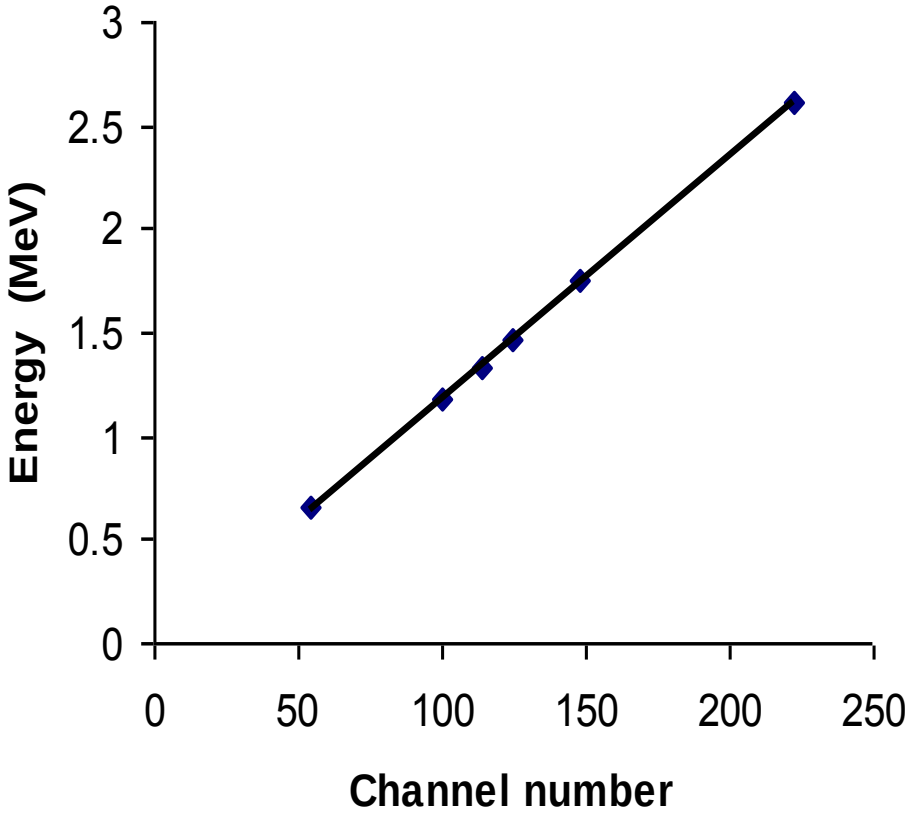


Figure 3.1 Energy - channel calibration curve.

It was noted that the efficiency of the detector also depends on the intrinsic condition associated with electronics of the detector; hence the statistic-based detectable limit (DL) of the counting system was calculated for each radionuclide in the samples. The detection efficiencies of the detector at different gamma energies were determined at a fixed sample geometry and matrix. The detector efficiency at specific gamma-ray energy obtained for the food samples is presented in Table 3.2 and displayed in Figure 3.2. Similarly, the efficiencies of the detector in the soil matrix samples were determined. The efficiency values are also presented in Table 3.2 and displaced in Figure 3.3

3.2 Determination of Detection Limit (DL)

The detection limit (Bq/kg) of a measuring system describes its operating capability without the influence of any sample. The detection limit (DL) expressed in Bq/kg, which is required to estimate the minimum detectable activity concentration in a sample, was obtained using Eq. 3.2 (Kitto et al., 2006)

$$DL = 1.96\left(\frac{\frac{B}{T} + SD_b^2}{k.\varepsilon.m}\right)^{1/2} \quad (3.2)$$

where SD_b is the estimated standard error of the net background count in the peak; T is the counting time (sec); ε is the counting efficiency (cps/Bq); m is the mass of the sample; k is the factor that converts cps (count per second) to Bq; B is the background count and 1.96 represent the 95% confidence level.

With the measurement system used in the present study, the detection limits (DLs) obtained were 17.3, 4.2 and 5.1 Bq/kg for ^{40}K, ^{226}Ra and ^{232}Th respectively. Any activity concentration values below these numbers are taken in this study as below detection limit (BDL) of the detector.

3.3 Sampling

3.3.1 Food Sampling

The food sampling in this study covered old tin mining towns (Bisichi, Bukuru and Ropp) in Jos, north central of Nigeria and (Osu, Awala and Itoko) in Abeokuta, southwestern of the country. Mixed farming is being practiced in almost all the farms where food crop samples were collected for the study. The local food crops grown on farmlands in the two

Table 3.2 Detector efficiency at specific gamma-ray energy

Sample Type	Radionuclides	Energy E (MeV)	Gamma-yield I_γ (%) (IAEA,1996)	Efficiency $\varepsilon \times 10^{-3}$(cps/Bq)
Food matrix				
	^{137}Cs	0.662	85.2	10.226
	^{40}K	1.460	10.7	7.499
	^{214}Bi (^{226}Ra)	1.764	15.9	6.660
	^{208}Tl(^{232}Th)	2.614	35.8	4.779
Soil matrix				
	^{137}Cs	0.662	85.2	11.200
	^{40}K	1.460	10.7	4.400
	^{214}Bi (^{226}Ra)	1.764	15.9	2.710
	^{208}Tl(^{232}Th)	2.614	35.8	1.410

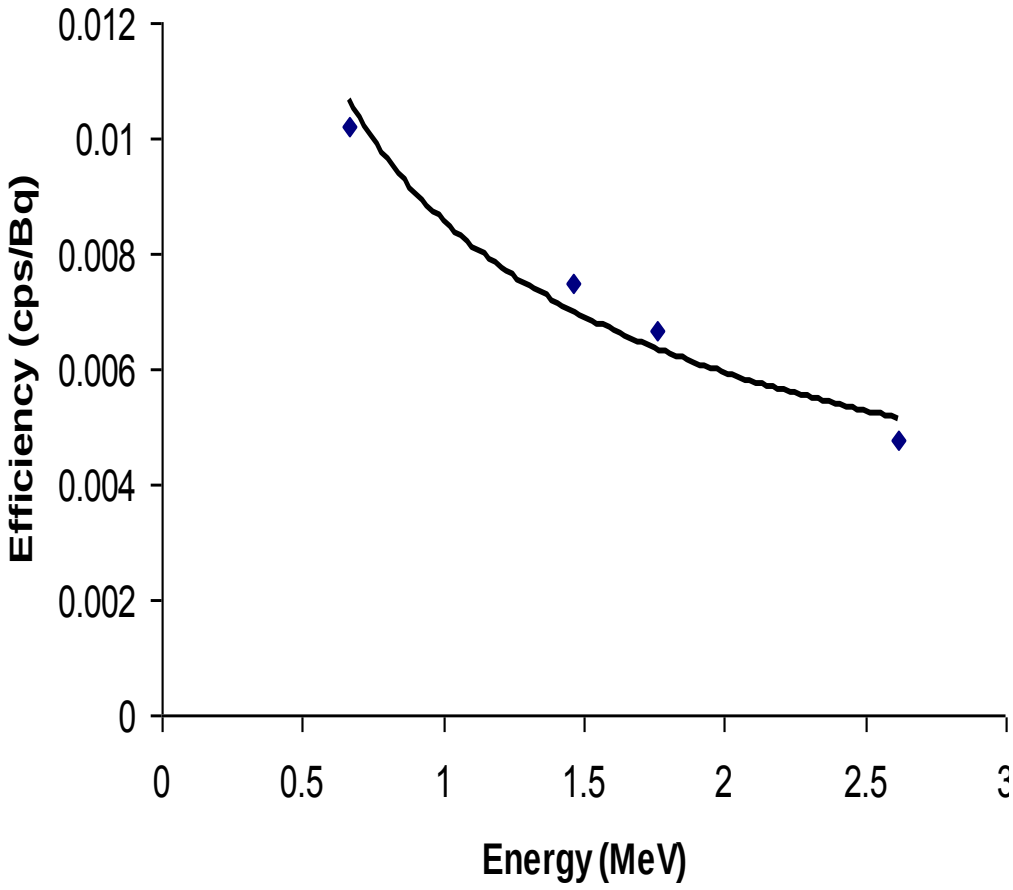


Figure 3.2 Efficiency calibration curve for reference food sample.

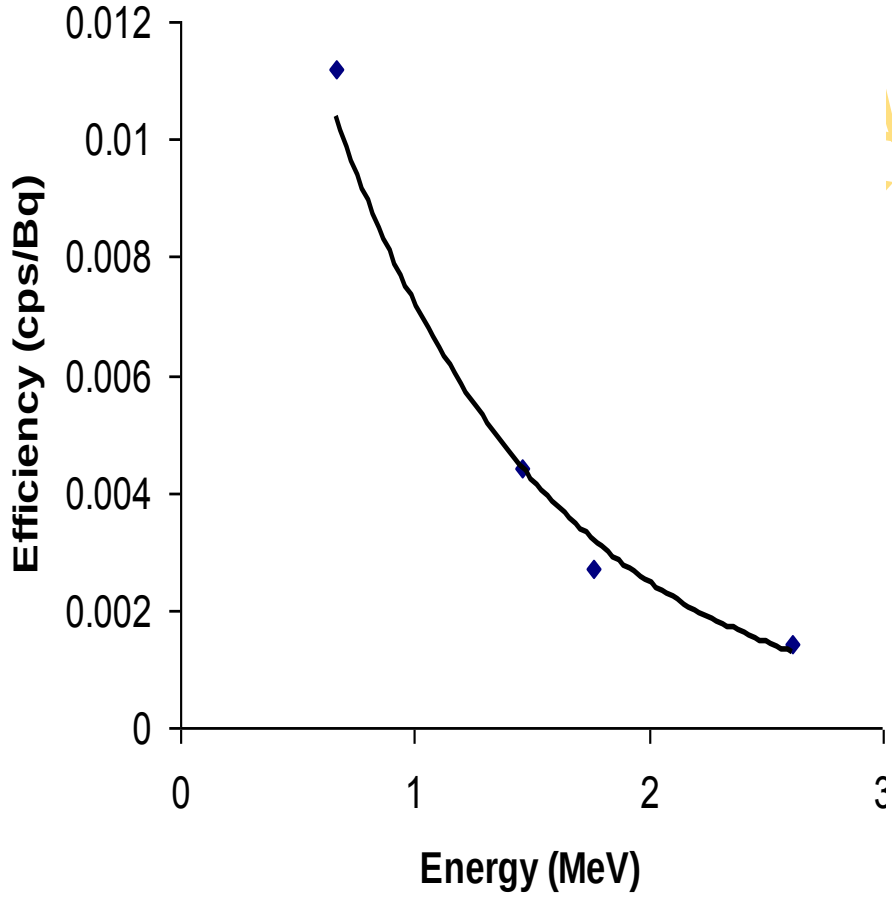


Figure 3.3 Efficiency calibration curve for reference soil sample.

areas of study were identified. In order to ensure adequate and good coverage, each sampling site was divided into six sub-areas of about 3.0 km^2 in size. The range of food items identified could not be fully collected at each sampling site since no single sub-area contained all the food types grown in the whole area. However, efforts were made to ensure some collection of food crop samples identified in the study areas. The sampling was carried out during harvesting period to facilitate collection of food samples directly from the farmlands. The cereals, beans, tomato, okra, pepper and garden-egg food crops were plucked; the tubers and groundnut were uprooted, from each of the farms where food samples were collected. Between 0.5 and 1.0 kg of each of the food sample was collected at each sampling site. The food samples collected from various farms were carefully packed in polythene bags and transported to the laboratory for preparation and spectroscopic analysis. The different food samples collected along with number of each sample from both Jos and Abeokuta are presented in Table 3.3.

3.3.2 Soil Sampling

Farm soil samples including the organic and inorganic particles in the soil at the point of sampling were collected to a depth of 150mm and a surface area of about 250 sq. mm from four different points in the farm where food samples were collected. Thereafter, the soil samples collected were thoroughly mixed together to provide a representative sample for that site. A total number of 106 soil samples were randomly collected, 59 from Bisichi, Bukuru and Ropp in Jos and 47 from Itoko, Osu and Awala in Abeokuta. The number of farm soil samples collected was less than the number of food samples because of mixed the farming that is being practiced in the farms where samples were collected. The soil samples from various farms were carefully packed in polythene bags. The samples were thereafter taken to laboratory for preparation and spectroscopic analysis.

3.4 Sample Preparation

3.4.1 Food Samples:

The prepared food samples represent the raw foodstuffs that are sold in various local markets to consumers. Since the study is focused on human ingestion of foods grown and consumed by the population in the study areas only the edible portions of the food samples were prepared for spectroscopic analysis (Jibiri and Agomuo, 2007). For instance, cassava, yam and cocoyam tubers were peeled. The edible parts were thereafter sliced and air dried to

Table 3.3: The types and number of food samples collected

Food Types	*Botanical Names*	Jos	Abeokuta	Total
CEREALS				
Maize	*Zea mays*	22	20	42
Millet	*Pennisetum americanum*	12	-	12
Acha	*Digitaria exilis stapf*	10	-	10
Dyare		7	-	7
Guinea Corn	*Sorghum bicolor*	10	-	10
Rice	*Oryza Sativa*	-	10	10
TUBERS				
Yam	*Dioscorea spp.*	10	10	20
Cocoyam	*Colocasia esculenta*	10	10	20
Cassava	*Manihot esculenta*	12	15	27
TUBEROUS VEGETABLES				
Sweet Potato	*Lpomoea batatas*	10	-	10
Irish Potato	Solanum tuberosum	5	-	5
LEGUME				
Soya Beans	*Glycine max.*	5	-	5
Local Beans	*Phaseolus vulgaris*	5	-	5
Groundnut	*Arachis hypogaea*	10	-	10
GENERAL VEGETABLE				
Tomato	*Lycopersicon esculentum*	10	-	10
Okra	*Abelmoschus esculentus*	10	-	10
Pepper	*Capsicum spp.*	10	-	10
Garden-egg	*Solanum gilo*	10	-	10
LEAFY VEGETABLE				
Kuca		10	-	10

a constant weight, pulverized to pass through a 2.0 mm sieve so as to have the same matrix as the standard food sample then homogenized and transferred into uncontaminated calibrated geometry sample containers of uniform sizes (60 mm in height by 65 mm in diameters). The containers were then sealed and kept for a period of about 28 days (4 weeks) to allow for secular equilibrium between ^{222}Rn and its short-lived daughters prior to gamma spectroscopy (Pyle and Clulow, 1997).

3.4.2 Soil Samples:

The soil samples were dried for several days at room temperature until a constant mass was reached. Thereafter, the soil samples were crushed and pulverized, sieved with a 2.0 mm mesh sieve. The sieved soil samples were also transferred into uncontaminated empty cylindrical plastic containers of uniform size (60 mm in height by 65 mm in diameter) sealed and kept for a period of about four (4) weeks like the food samples.

3.5 Radioactivity Determination in the Samples

A gamma spectrometry system consisting of a 76 mm by 76 mm NaI (Tl) detector (Model No 802-series, Canberra Inc.) couple to a Canberra series 10 plus Multi Channel Analyzer (MCA) (Model No 1104) through a preamplifier base was used for analysis in the study. The detector has a poor energy resolution of about 8% at energy of 0.662 MeV. This is considered sufficient to distinguish the gamma energies of interest in the study. The photons emitted by the samples would sufficiently be discriminated if their emission probability and their energy were high enough and the surrounding background continuum was low enough.

Therefore, the activity concentration of ^{214}Bi (determined from its 1.760 MeV gamma ray peak) was chosen to provide an estimate of ^{226}Ra in the food samples, while that of the daughter radionuclide ^{208}Tl (determined from its 2.615 MeV gamma ray peak) was chosen as an indicator of ^{232}Th. ^{40}K was determined by measuring the 1.460 MeV gamma rays emitted during the decay of ^{40}K. The presence of ^{137}Cs isotope in any sample is an indicator for any potential environmental contamination due to nuclear accidents and weapon tests (Sutherland and deJong, 1990). The standard reference food sample used for the efficiency calibration was obtained from the International Atomic Energy Agency, IAEA traceable to source Ref No IAEA-152. While the standard reference soil sample

used for efficiency calibration was from Rocketdyne Laboratories California, USA, traceable to a mixed standard gamma source (Ref No 48722-356) by Analytic Inc., Atlanta, GA, USA.

The detector is housed tightly inside a lead shield that has almost the same diameter as the sample containers. Each of the food or soil sample container was placed on top of the detector and measured for a period of 36000 seconds (10 hrs). The net area under the corresponding peaks in the energy spectrum was determined by subtracting counts due to background sources from the total area of the peaks. Using the net area under the peak, the activity concentrations in the samples were obtained using Equation (3.3) (Farai and Ademola, 2001, Jibiri and Ajao, 2005, and Jibiri and Bankole, 2006)

$$C(Bq/kg)=\frac{C_k A}{A_k M} \qquad (3.3)$$

where C_k is the activity concentration of the radionuclide in a standard reference sample having the same geometry or matrix as the investigated sample expressed in (Bq/kg), A_k is the net area of the peak in the reference sample spectrum and A is the net area of the corresponding peak in the sample spectrum and M is the mass of the sample being analyzed.

Using Equation 3.3, the activity concentrations in the food crops and soil samples were determined. The results are presented in chapter four.

CHAPTER FOUR

RESULTS

4.1 Activity concentrations in food crops from Jos and Abeokuta

The range and mean activity concentrations for ^{40}K, ^{226}Ra and ^{232}Th radionuclides in the food items from Jos and Abeokuta are presented in Tables 4.1 and 4.2 respectively. The activity concentration of the radionuclides in the common food samples from Jos and Abeokuta are also presented in Table 4.3. The errors in the measured activity concentrations are the standard deviations obtained for each food type. It represents the spread across the measured activity concentrations values in each food type.

4.2 Activity concentrations in farm soil samples

The range and mean activity concentrations of ^{40}K, ^{226}Ra and ^{232}Th radionuclides in farm soil samples in Jos and Abeokuta are presented in Table 4.4. The errors in the values of the activity concentrations are the standard deviations.

4.3 Effective dose due to ingestion of foodstuffs

Effective dose is a useful concept in the radioactivity measurement that enables the radiation doses from different types of radiation and the doses by different organs to be added. It is based on the risks of radiation induced health effects and the use of International Commission on Radiological Protection (ICRP) metabolic model provides relevant conversion factors that permit the calculation of effective doses from the total activity concentrations of the radionuclides measured in food items (ICRP, 1994 and 1996). The estimation of the radiation induced health effects associated with intake of radionuclides in the body is proportional to the total dose delivered by the radionuclides on accumulation in the various body organs. The radiation dose delivered when food is taken also known as effective dose is obtained by measuring how much is the activity concentration (Bq kg^{-1}) of the radionuclide in the food; multiplying it by how much food is consumed over a period of time (kg d^{-1} or kg y^{-1}) and then by a dose conversion physical factor (Sv Bq^{-1}) which gives an indication of how much dose is caused by a unit radioactivity in the given body organ.

According to Till and Moore (1988), the ingested dose is given by:

$$H_{T,r} = \left(U^{Bl} \times C_r^{Bl} + U^{Pf} \times C_r^{Pf} + U^{Mi} \times C_r^{Mi} + ...\right) \times g_{T,r} \qquad (4.1)$$

However Equation 5.1 can be expressed as:

$$H_{T,r} = \sum \left(U^i \times C_r^i\right) \times g_{T.r} \qquad (4.2)$$

Table 4.1: The Range and mean activity concentrations of radionuclides in food crops (Bq/kg, dry mass) from parts of Jos

Food Types	^{226}Ra(Bq/kg)		^{232}Th(Bq/kg)		^{40}K(Bq/kg)	
	Range	Mean±σ	Range	Mean±σ	Range	Mean±σ
CEREALS						
Maize	4.4-72.2	32.3±12.5	BDL-72.2	20.2±1.1	31.1-762.0	239.6±51.9
Millet	4.6-39.9	17.5±5.1	BDL-56.8	21.6±10.6	98.9-359.5	177.9±14.6
Acha	BDL-20.9	17.3±0.5	BDL-50.0	18.6±1.6	BDL-241.5	67.8±10.5
Dyare	BDL-4.7	2.4±1.1	BDL-8.1	4.1±3.2	BDL-179.4	89.7±25.3
Guinea Corn	BDL-62.8	31.9±5.3	BDL-83.8	24.6±6.7	85.9-930.9	399.7±69.6
TUBERS						
Yam	38.9-85.5	76.2±11.5	19.7-89.8	75.8±5.3	272.6-684.5	602.1±35.4
Cocoyam	BDL-55.1	39.3±15.1	BDL-49.0	37.2±7.2	BDL-1406.1	754.4±18.1
Cassava	27.4-45.3	31.0±10.6	22.8-28.4	23.4±4.6	220.0-539.6	475.7±19.4
TUBEROUS VEGETABLES						
Sweet Potato	23.6-55.7	31.8±12.2	31.3-45.4	37.5±9.9	215.4-632.6	389.1±26.1
Irish Potato	10.7-50.0	18.6±6.5	1.0-17.1	13.9±7.9	494.4-563.2	508.2±22.4
LEGUME						
Soya Beans	8.3-25.4	12.6±7.1	BDL-31.1	7.8±2.7	496.9-546.8	534.3±27.3
Local Beans	BDL-28.5	13.9±4.1	BDL-46.8	17.5±3.3	387.4-526.1	444.1±16.7
Groundnut	7.1-43.6	14.6±7.4	BDL-88.9	23.7±3.3	58.7-398.6	296.8±11.5
GENERAL VEGETABLE						
Tomato	13.9-32.0	18.4±8.5	9.6-18.6	11.9±3.7	158.9-856.5	333.3±28.7
Okra	BDL	BDL	BDL	BDL	BDL-639.0	213.0±19.4
Pepper	BDL-13.5	4.5±3.8	BDL	BDL	BDL-397.2	132.4±19.2
Garden-egg	BDL-64.2	32.1±19.2	BDL	BDL	BDL-244.6	122.3±22.2
LEAFY VEGETABLE						
Kuca	BDL-31.2	10.4±7.1	BDL	BDL	BDL-241.8	80.6±17.2

DL means below detection limit of the detector used in the spectral analysis of the radionuclides in the samples.

Table 4.2: The range and mean activity concentrations of radionuclides in food crops (Bq/kg, dry mass) from Abeokuta

Food Types	^{226}Ra(Bq/kg)		^{232}Th(Bq/kg)		^{40}K(Bq/kg)	
	Range	Mean±σ	Range	Mean±σ	Range	Mean±σ
CEREALS						
Maize	BDL-81.1	33.3±12.5	BDL-23.8	9.2±1.0	38.2-599.1	341.9±19.8
Rice	5.8-50.0	27.6±18.1	BDL-13.4	6.0±1.6	185.4-241.0	215.1±22.7
TUBERS						
Yam	4.9-55.9	32.0±15.4	BDL-26.5	9.7±7.6	407.1-1611.9	1048.1±36.4
Cocoyam	19.7-63.6	37.3±15.5	BDL-14.0	6.1±0.6	599.8-1648.3	990.5±34.4
Cassava	1.9-61.6	32.3±13.9	4.3-48.3	28.3±2.4	250.3-936.4	587.4±25.7

DL means below detection limit of the detector used in the spectral analysis of the radionuclides in the samples.

Table 4.3: The mean activity concentrations of radionuclides in common food samples from Jos and Abeokuta.

Food sample	Area	^{226}Ra (Bq/kg) Mean ±σ	^{232}Th (Bq/kg) Mean ±σ	^{40}K (Bq/kg) Mean ±σ
Maize	Jos	32.3±12.5	20.2±1.1	239.6±51.9
	Abeokuta	33.3±12.5	9.2±1.0	41.9±19.8
Yam	Jos	76.2±11.5	75.8±5.3	602.1±35.4
	Abeokuta	32.0±15.4	9.7±7.6	1048.1±36.4
Cocoyam	Jos	39.3±15.1	37.2±7.2	754.4±18.1
	Abeokuta	37.3±15.5	6.1±0.6	990.5±34.4
Cassava	Jos	31.0±10.6	23.4±4.6	475.7±19.4
	Abeokuta	32.3±13.9	28.3±2.4	587.4±25.7

Table 4.4: The range and mean activity concentrations due to radionuclides in farm soils from Abeokuta and the three mining areas in Jos

Site	Number of soil samples		^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)
Bitsichi	31	Range	67-471	93-2190	BDL-906
		Mean±σ	163±92	451±368	466±221
Bukuru	14	Range	80-157	BDL-247	614-1238
		Mean±σ	109±28	154±56	981±263
Ropp	14	Range	43-293	66-401	525-1854
		Mean±σ	129±65	147±75	1062±199
Abeokuta	47	Range	13-122	BDL-808	27-1329
		Mean±σ	65±29	184±205	411±341

DL means below detection limit of the detector used in the spectral analysis of the radionuclides in the samples.

where i denotes a food group, the coefficients U^i and C^i_r denotes the consumption rate (kg/yr) and activity concentration of the radionuclide (Bqkg^{-1}) respectively and $g_{T\,r}$ is the dose coefficient for intake by ingestion of radionuclide r (Sv Bq^{-1}). The values of $g_{T\,r}$ for ^{40}K, ^{226}Ra, ^{232}Th and ^{137}Cs are respectively, 5.9 x 10^{-9} Sv Bq^{-1}, 4.8 x 10^{-8} Sv Bq^{-1}, 2.3 x 10^{-7} Sv Bq^{-1} and 1.3 x 10^{-8} Sv Bq^{-1} respectively for members of the public (adult) (ICRP, 1994; 1996; RIFE, 2005). These conversion factors were used to determine, the effective doses due to dietary intake of radionuclides for Jos and Abeokuta respectively. The food consumption rate (U^i) statistics used for the different food crops in Nigeria was obtained from the Federal Office of Statistics (FOS) (Table 4.5). In this study, the calculation of individual doses and risks from ingestion pathways carried out were based on the assumption that all food consumed is produced at the point of consumption and that the required amount of food is produced in the given location. In essence the consumption of such foodstuff is sustained wholly by local sources.

In estimating the doses to individuals in agricultural food products, it is important to consider the peculiarity of the food availability to such individuals and the nature of the environment from which he derives the food products. The three types of individual usually considered are:

(i) A control individuals whose diet consists of food grown on farmland free from natural radioactivity

(ii) A local individual who obtains some percentage of his food from high background radiation farmland.

(iii) A theoretical maximum exposed individual whose food is obtained solely from high background radiation farmland.

Based on the conditions that the study involves high background radiation areas the assessment of dose is based on the assumptions of (iii) that the individuals derives all its nutritive requirement from the crops analyzed and that he solely resides in that environment. However, a maximum exposed individual does not exist in reality, but from radiation protection perspective, conservative estimate of dose is important in relation to Protective Action Guide (PAG) and other scenarios such as planning and legislation of food policy and administration (Fernandez et al., 2004). Protective Action Guide (PAG) is referred to as an action or measure taken to avoid exposure to radiation that would occur when ingestion of foods contaminated with radioactive materials due to local or international releases in the future. The estimated total effective dose on ingestion of food crops from Jos and Abeokuta are presented in Tables 4.6 and 4.7 respectively.

Table 4.5: Mean annual consumption (MAC) values in kilogram per person

Food Type	Consumption rate (U)[i] (kg/Person[a])
Maize	20.67
Millet	36.24
Rice	26.35
Guinea corn	44.70
Other cereals	0.06
Cassava	115.46
Irish Potato	3.24
Sweet Potato	14.35
Yam	75.15
Other roots	6.50
Beans	0.02
Soya Beans	2.58
Groundnut	2.76
Tomatoes	7.19
Pepper	8.06
Vegetables	60.50

[a] Data was collected from the Federal Office of Statistics (FOS), Nigeria (2006).

4.4 Absorbed dose rate due to the soil samples from the farmlands

The important quantity to assess when considering radiation risk to a bio-system is the absorbed dose rate. The absorbed gamma dose rate, D (nGy h^{-1}) in air at 1 m above the ground level due to the concentration of ^{238}U, ^{232}Th and ^{40}K in the soil samples in each site was calculated using the equation (UNSCEAR, 2000):

$$D = a.C_U + b.C_{Th} + c.C_K + d.C_{Cs} \quad (4.3)$$

where a is the dose rate per unit ^{238}U activity concentration (4.27 x 10^{-10} Gy h^{-1}/Bq kg^{-1}), C_U is the concentration of ^{238}U in the sample (Bq kg^{-1}), b is the dose rate per unit ^{232}Th activity concentration (6.62 x 10^{-10} Gy h^{-1}/Bq kg^{-1}), C_{Th} is the concentration of ^{238}U in the sample (Bq kg^{-1}), c is the dose rate per unit ^{40}K activity concentration (0.43 x 10^{-10} Gy h^{-1}/Bq kg^{-1}), C_K is the concentration of ^{40}K in the sample (Bq kg^{-1}), d is the dose rate per unit ^{137}Cs activity concentration (0.30 x 10^{-10} Gy h^{-1}/Bq kg^{-1}) and C_{Cs} is the concentration of ^{137}Cs in the sample (Bq kg^{-1}). Since Caesium -137 was not detected in any of the samples the last term in equation 4.3 was assumed to be zero. Using equation 4.3 the absorbed dose rate due to the soil samples from Jos and Abeokuta are presented in Table 4.8

4.5 Effective dose rate due to soil samples from the farmlands

There are two additional factors that must be considered in assessing or determining the outdoor effective dose rate to the populace from the calculated absorbed gamma dose rate. The first is a factor which converts Gy to Sv that accounts for the biological effectiveness of the dose in causing damage in human tissue. The second is the occupancy factor that specifies the proportion of the total time spent outdoors.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recommended 0.7 Sv Gy^{-1} as the first factor and 0.2 and 0.8 as outdoor and indoor occupancy factors respectively. This second factor implies that the average individual spends only 4.8 h (about 5 h per day) outdoors. Adejuwon, (2002) reported that an individual farmer is expected to spend averagely about 8 hrs. per day in the farm; however, about 10 hrs. per day is spent by farmers from the study areas and generally for peasant farmers in the country. However, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recommended value of 0.2 as outdoor occupancy factor is considered in the present work.

Table 4.6: Estimated total effective dose (μSvy^{-1}) from ingestion of food items from Jos

Food types	No of sample	Range	Mean±σ
Maize	22	20.3-3597.0	157.3±18.1
Millet	12	50.4-619.7	248.5±29.1
Acha	10	1.8-8.4	3.3±1.4
Dyare	5	0.4-1.9	1.0±0.3
Guinea corn	10	53.4-1241.8	426.8±57.9
Yam	10	601.7-2164.1	1852.0±43.1
Cocoyam	10	9.6-144.4	968.0±39.1
Cassava	12	907.2-1372.8	1117.3±36.3
Sweet Potato	10	137.8-240.9	178.6±10.4
Irish Potato	5	11.9-31.3	23.0±7.3
Soya Beans	5	13.1-29.9	14.3±5.6
Local Beans	5	0.07-0.3	0.2±0.1
Groundnut	10	5.1-68.7	21.8±14.3
Tomato	10	27.4-78.1	40.2±9.3
Okra	10	83.2-228.0	153.1±13.4
Pepper	10	17.9-24.0	22.2±1.7
Garden-egg	10	89.3-273.8	207.8±25.5
Kuca	10	78.3-176.9	129.9±19.7

Table 4.7: Estimated total effective dose (μSv/y) from ingestion of food items from Abeokuta.

Food types	No of sample	Range	Mean±σ
Maize	20	4.0-266.7	118.5±18.9
Rice	10	55.2-181.9	104.7±16.6
Yam	10	347.7-1374.4	747.8±19.1
Cocoyam	10	29.2-104.0	58.7±15.7
Cassava	15	295.2-2261.9	1064.6±32.3

The effective dose rate due to soil samples from the farmlands in each site was calculated using the equation (UNSCEAR, 2000):

$$H_R = D \times 0.2 \times 0.7 \times 8766 \quad (4.4)$$

where D is the absorbed gamma dose rate in (nGy h^{-1}); 0.2 is the occupancy factor; 0.7 $SvGy^{-1}$ is the conversion factor recommended by UNSCEAR and 8766 is in hr/yr. Using equation 4.4, the mean gamma effective dose due to the activity concentrations of the radionuclides in the farm soil from the study areas were calculated. The results are also presented in Table 4.8.

4.6 Life Time Cancer risks due to ingestion of food crops

Cancer is the rapid creation of abnormal cells that grow beyond their boundaries, invade adjoining parts of the body and later spread to other organs. A life time cancer risk is defined in this work as an estimate of the risk to member of a population dying from cancer as a result of intake of a radionuclide in food samples from the study areas (EPA, 1999). The life time cancer risks associated with intake of food crops was determined from the cancer risk coefficients for ingestion of radionuclides and per-capital intake of the radionuclides given by EPA (1999) and UNSCEAR (2000):

$$R = \sum r_i I_i \quad (4.5)$$

where

$$I_i = A_i C T \quad (4.6)$$

where r_i is the cancer risk coefficient for ith radionuclide, I_i is the per-capital activity intake of the radionuclide, A_i is the activity concentration of the ith radionuclide, C is the food consumption rate and T is the average life expectancy. The average life expectancy at birth in Nigeria is 45.5 years (WHO, 2008) and the food consumption statistics used were obtained from Federal Office of Statistics and Food Agriculture Organization (FOS/ FAO, 2006). The value of risk coefficients, r for ^{226}Ra, ^{232}Th and ^{40}K are 9.56×10^{-9} Bq^{-1}, 2.45×10^{-9} Bq^{-1} and 5.89×10^{-10} Bq^{-1} (EPA, 1999 and UNSCEAR, 2000) respectively. Using these risk coefficients and the calculated activity intake of the radionuclides, the cancer risks were evaluated. The results are presented in Tables 4.9 and 4.10 for Jos and Abeokuta respectively.

Table 4.8: The range and mean absorbed dose and effective dose rates due to natural radionuclides in farm soils from the three mining areas of Jos and Abeokuta

Site	Number of soil samples		^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	Absorbed dose (nGy/h)	Effective dose rate (mSv/yr)
Bitsichi	31	Range	67-471	93-2190	BDL-906	93-653	0.11-2.02
		Mean±σ	163±92	451±368	466±221	350±270	0.43±0.33
Bukuru	14	Range	80-157	BDL-247	614-1238	57-282	0.07-0.35
		Mean±σ	109±28	154±56	981±263	194±59	0.24±0.08
Ropp	14	Range	43-293	66-401	525-1854	112-362	0.14-0.44
		Mean±σ	129±65	147±75	1062±199	196±70	0.24±0.08
Abeokuta	47	Range	13-122	BDL-808	27-1329	23-580	0.03-0.71
		Mean±σ	65±29	184±205	411±341	167±140	0.21±0.18

Table 4.9: Cancer risk due to ingestion of food crop from Jos

Food crop	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K(Bq/kg)	Cancer risk
Maize	32.3±12.5	20.2±1.1	239.6±51.9	4.25E-04
Millet	17.5±5.1	21.6±10.6	177.9±14.6	5.36E-04
Acha	17.3±0.5	18.6±1.6	67.8±10.5	6.85E-07
Dyare	2.4±1.1	4.1±3.2	89.7±25.3	2.34E-07
Guinea corn	31.9±5.3	24.6±6.7	399.7±69.6	1.22E-03
Yam	76.2±11.5	75.8±5.3	602.1±35.4	4.34E-03
Cocoyam	39.3±15.1	37.2±7.2	754.4±18.1	2.69E-04
Cassava	31.0±10.6	23.4±4.6	475.7±19.4	3.33E-03
Sweet Potato	31.8±12.2	37.5±9.9	389.1±26.1	4.08E-04
Irish Potato	18.6±6.5	13.9±7.9	508.2±22.4	7.54E-05
Soya Beans	12.6±7.1	7.8±2.7	534.3±27.3	5.33E-05
Local Beans	13.9±4.1	17.5±3.3	444.1±16.7	3.98E-07
Groundnut	14.6±7.4	23.7±3.3	296.8±11.5	4.68E-05
Tomato	18.4±8.5	11.9±3.7	333.3±28.7	1.31E-04
Okra	4.2± 2.55	2.6±1.2	213.0± 19.4	4.73E-04
Pepper	4.5± 3.8	2.6±1.2	132.4±19.2	4.67E-05
Garden egg	32.1±19.2	□□□□□□□□□□□□□□□□□□□□2.6±1.2		
	122.3±22.2	1.06E-03		
Kuca	10.4± 7.1	2.6±1.2	80.6± 17.2	4.22E-04
			Total	1.28E-02

Table 4.10: Cancer risk due to ingestion of food crops from Abeokuta

Food crop	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	Cancer Risk
Maize	33.3±12.5	9.2±1.0	341.9±19.8	5.10E-04
Rice	27.6±18.1	6.0±1.6	215.1±22.7	4.86E-04
Yam	32.0±15.4	9.7±7.6	1048.1±36.4	3.24E-03
Cocoyam	37.3±15.5	6.1±0.6	990.5±34.4	2.82E-04
Cassava	32.3±13.9	28.3±2.4	587.4±25.7	3.80E-03
			Total	8.32E-03

4.7 Life Time Cancer risks due to exposure from farm soil radioactivity.

The cancer risks due to the external radiation exposure from farm soils were evaluated using carcinogenicity radionuclide slope factors for environmental exposure to radionuclides by United States Environmental Protection Agency and the average life expectancy (EPA, 1999) and (UNSCEAR, 2000):

$$R = \sum r_i AT \tag{4.7}$$

where A is the activity concentration in Bq/kg, r_i is the cancer mortality risk coefficient for ith radionuclide and T is the average life expectancy. The value of r for ^{226}Ra, ^{232}Th and ^{40}K are 1.33 x 10^{-17}kg/Bq-s, 1.97x10^{-19}kg/Bq-s and 4.66 x 10^{-16}kg/Bq-s respectively. Using equation 4.7 and the life expectancy of 45.5 years for Nigeria (WHO, 2008) and the cancer risk coefficients substituted, the cancer risks due to external radiation exposure from the farm soils were evaluated. The results are presented in Tables 4.11. The total cancer risks, R_T due to the radiation exposure from farm soils and food ingestion was evaluated using:

$$R_T = R_S + R_F \tag{4.8}$$

where R_S is the cancer risks due to radioactivity in soils and R_F is the cancer risks due to radioactivity in food ingestion.

4.8 Soil to food crop transfer factor of ^{40}K, ^{226}Ra and ^{232}Th in the study areas

Migration and accumulation of contaminants including radionuclides in the soil-plant system is an assessment models commonly utilized in a soil-plant activity concentration ratio, referred to as transfer factor (TF). It is used to estimate the transportation of radionuclides through the food chain. This ratio describes the amount of radionuclides expected to enter a plant or food crop from soil. Factors such as soil characteristics, climatic conditions, type of plants, physic-chemical form of the radionuclides and the interfering element can all influence the transfer factor (TF) values (Bettencourt et al., 1988). Transfer factors which are the ratios of activity concentrations in food crops to the activity in the soil can be used as an index for the accumulation of radionuclides in food crops (Yanagisawa 1992; Whicker, 1999). Various studies on natural radionuclides transfer or pathway mechanism to plant and human have been reported in the literatures (Mitchell, 1974; ICRP, 1993; Gaso 2000; Marko and Smodis, 2011). According to Uchida and Tagami (2009), the transfer factor (TF) is given by:

$$TF = \frac{A_F}{A_S} \qquad (4.9)$$

where A_F is the activity concentration of radionuclides in edible parts of food crop and A_S is the activity concentration of radionuclides in soil.

In this study, the emphasis was particularly to evaluate radiation exposure to the population due to food ingestion and external dose from farm soils in the farm lands considered. The requisite procedure for considering soil to food crops transfer factor study was not followed. However, some soil samples which were collected directly from the same sport as the food crops samples have been used for transfer factor estimations for Jos area only. This could not be done for Abeokuta samples since the requisite sampling techniques were not followed. The activity concentrations of ^{40}K, ^{226}Ra and ^{232}Th with the standard errors in the food crops and the corresponding activities in the soil samples from same spots in Jos are presented in Table 4.12.

Table 4.11: Cancer risk due to radiation exposure from the farm soil in the study areas.

Site	Number of soil sample	Range	Cancer risk
Bisichi	31	1.41×10^{-5}-6.11×10^{-4}	3.15×10^{-4}
Bukuru	14	4.03×10^{-4}-1.01×10^{-3}	4.44×10^{-4}
Ropp	14	2.18×10^{-4}-1.24×10^{-3}	6.16×10^{-4}
Abeokuta	47	1.85×10^{-5}-8.90×10^{-4}	2.51×10^{-4}

Table 4.12: Activity Concentrations of radionuclides in food and soil samples collected from same spots in parts of Jos.

Food Type	Concentration in food(Bq/kg)			Concentration in soil (Bq/kg)		
	^{40}K	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th
Guinea corn						
Spot 1	587.1±33.6	52.7±22.1	83.8±6.9	436.5±43.5	116.4±24.7	128.9±9.8
Spot 2	130.8±8.7	31.5±2.7	17.0±1.6	369.6±34.6	304.1±19.8	573.5±34.9
Spot 3	411.6±32.5	42.6±14.5	43.3±12.3	830.7±38.3	87.0±20.0	85.2±6.3
Spot 4	296.0±17.5	42.1±14.7	17.5±2.1	1109.7±42.7	48.3±18.9	65.8±6.9
Spot 5	468.0±22.5	46.2±19.3	19.2±1.9	1515.1±49.7	195.5±22.3	114.6±7.8
Spot 6	601.8±23.7	30.2±16.4	2.6±1.1	1393.4±54.3	135.5±23.5	151.1±9.8
Spot 7	112.6±17.8	20.9±5.2	25.1±4.3	913.4±36.2	123.7±16.9	319.0±15.0
Maize						
Spot 1	110.5±7.4	11.3±2.4	3.0±1.1	329.4±31.2	88.2±24.5	236.2±11.4
Spot 2	61.8±4.4	13.7±9.7	2.6±2.1	708.8±45.2	90.7±20.1	247.8±12.1
Spot 3	139.0±11.0	16.0±7.9	39.5±18.4	390.9±29.7	67.1±22.0	144.4±9.3
Spot 4	38.4±21.9	37.4±11.9	28.6±17.5	351.7±33.2	81.8±17.5	247.0±12.4
Spot 5	126.5±9.8	4.4±1.9	56.0±19.2	250.1±23.0	127.4±20.1	244.7±11.3
Spot 6	121.3±7.7	16.4±3.6	72.2±5.1	630.9±34.1	132.3±23.2	225.4±10.5
Spot 7	90.8±6.5	41.4±14.6	45.4±19.0	760.9±39.0	113.6±23.3	238.3±11.7
Spot 8	40.2±3.0	32.9±13.7	13.3±4.9	734.3±39.3	146.3±23.0	124.2±8.3
Spot 9	31.1±2.5	58.8±21.3	45.2±4.0	1500.4±47.1	98.7±18.4	114.6±7.7
Spot 10	503.1±23.9	36.6±15.0	9.8±1.3	941.6±36.3	104.9±29.2	155.7±9.3
Yam						
Spot 1	272.6±14.8	38.9±14.5	19.7±1.8	652.9±34.2	201.9±24.3	251.9±11.1
Spot 2	596.8±23.9	48.7±15.6	38.8±2.7	1154.4±42.6	122.2±16.3	165.7±9.4
Spot 3	497.4±17.5	39.8±19.1	22.7±1.4	1854.0±51.7	167.9±27.2	149.9±9.3
Spot 4	627.3±22.7	41.6±17.3	21.6±3.3	1240.5±43.7	115.3±21.2	153.2±10.2
Spot 5	396.1±80.7	45.3±23.2	20.1±13.9	743.0±35.7	182.3±39.1	124.1±11.9
Spot 6	346.7±34.4	67.3±19.7	54.3±15.8	1921.2±53.0	215.3±25.3	317.1±14.6

Table 4.12: Continues.

Food type	Concentration in food(Bq/kg)			Concentration in soil (Bq/kg)		
Cassava	^{40}K	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th
Spot 1	210.7±52.1	27.0±5.1	22.8±2.4	749.2±33.5	57.9±18.3	151.2±9.1
Spot 2	370.2±31.2	40.5±24.3	23.5±4.8	843.1±37.2	93.1±21.2	169.1±12.5
Spot 3	304.7±39.3	38.2±5.9	26.1±5.6	1213±45.7	96.3±18.7	243.2±12.3
Spot 4	315.5±45.9	28.3±17.0	21.8±11.3	941.2±41.3	86.4±14.9	166.4±10.7
Spot 5	335.7±67.8	31.7±15.6	25.3±9.8	1145.9±41.2	213.1±31.4	154.3±8.8
Spot 6	267.2±58.4	33.8±22.3	28.0±12.7	1741±49.1	169.6±37.1	269.2±14.1

CHAPTER FIVE
DISCUSSION AND CONCLUSION

5.1 Activity concentrations in food crops from Jos

The radionuclides detected in all the food crop samples analyzed indicated only the presence of natural radionuclides; ^{40}K, ^{226}Ra and ^{232}Th. No artificial radionuclide was detected in any of the food analyzed. This apparently indicates that the radioactivity in the food samples from the study areas is due to natural radionuclides or a limitation in the methodology employed. Figures 5.1, 5.2 and 5.3 are the histograms that illustrated the distribution of ^{40}K, ^{226}Ra and ^{232}Th in all the food crops from Jos.

5.1.1 Activity concentrations in cereal crops

As could be seen from Table 4.1, the activity concentration of ^{40}K was highest in the entire food samples investigated. Similar findings have been reported by other authors (Badran et al., 2003, Hernandez et al., 2004). As shown in Tables 4.1 the highest mean activity concentration of 399.7 Bq/kg in ^{40}K was measured in Guinea corn and the lowest concentration of 67.8 Bq/kg was obtained in acha (hungry rice). In maize the highest ^{226}Ra concentration was 32.3 Bq/kg while in Dyare it was 2.4 Bq/kg. In all the cereals, Guinea corn has the highest ^{232}Th activity concentration of 24.6 Bq/kg while Dyare had the lowest value of 4.1 Bq/kg.

The activity concentrations in maize in the present study are higher by a factor of about five when compared to the values of 48.79Bq/kg for ^{40}K, 13.2 Bq/kg for ^{226}Ra and 4.08 Bq/kg for ^{232}Th in maize reported by Mlwilo et al., (2007). The measured activity concentrations obtained in cereal food crops in the present study are observed to be about ten times higher in magnitude than those reported for cereals from Akure southwestern region of Nigeria by Arogunjo (2003) where the radioactivity levels varied from 36.4 to 186.9 Bq/kg for ^{40}K, 0.2 to 1.4 Bq /kg for ^{226}Ra and 0.3 to 1.8 Bq/kg for ^{232}Th.

5.1.2 Activity concentrations in tuber food crops

The values of activity concentrations in the tuber food crops as presented in Table 4.1 showed that the highest concentrations of ^{40}K in cocoyam, yam and cassava were 754.4 Bq/kg, 602.1 Bq/kg and 475.7 Bq/kg respectively while the lowest values of ^{232}Th in cassava, cocoyam and yam were 23.4Bq/kg, 37.2Bq/kg and 75.8Bq/kg respectively. The value of 107.0Bq/kg for ^{232}Th concentration in tuber reported by Shanthi, et. al (2009) was higher than

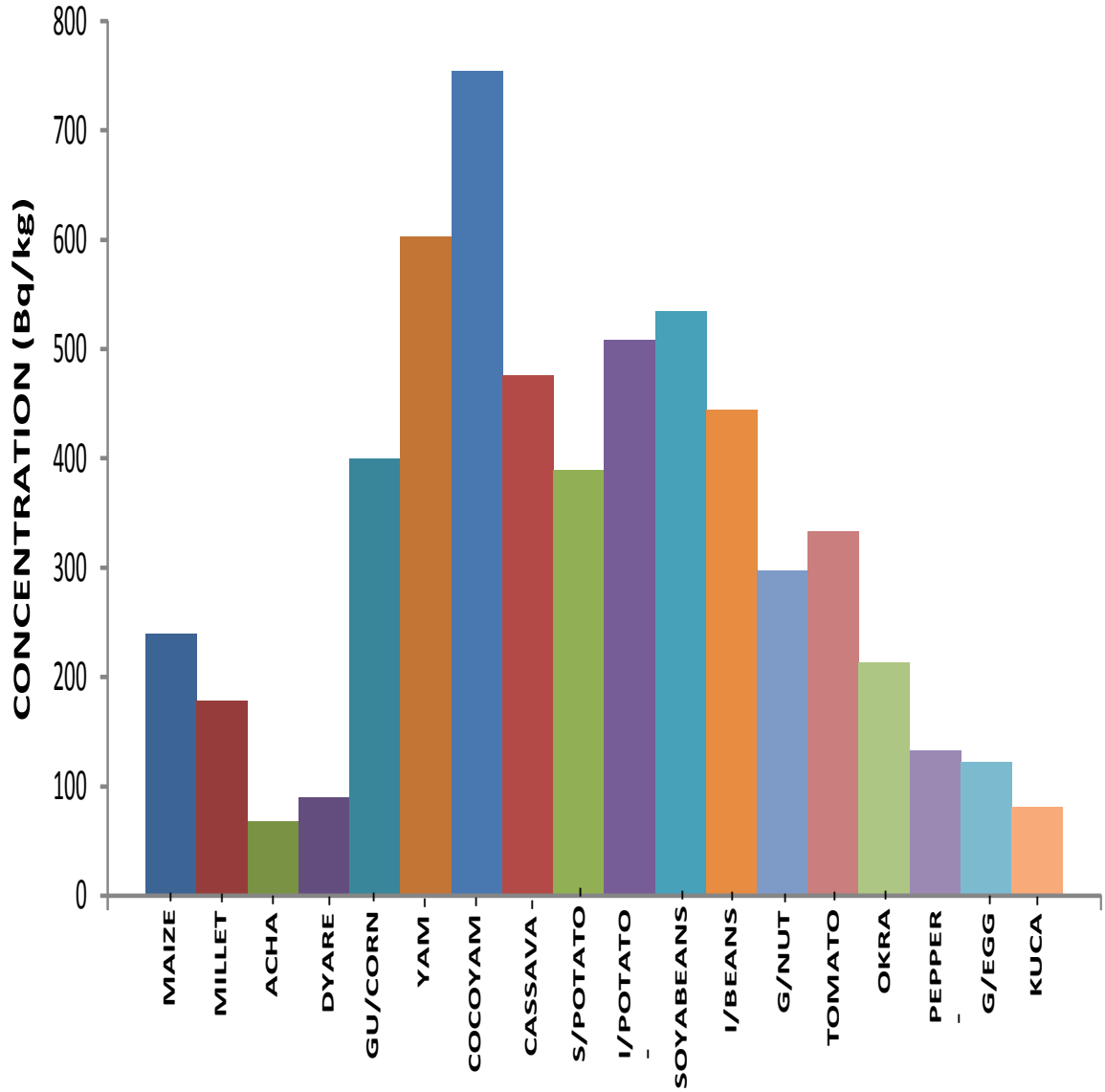


Figure 5.1: Distribution of ^{40}K in food crop samples from parts of Jos.

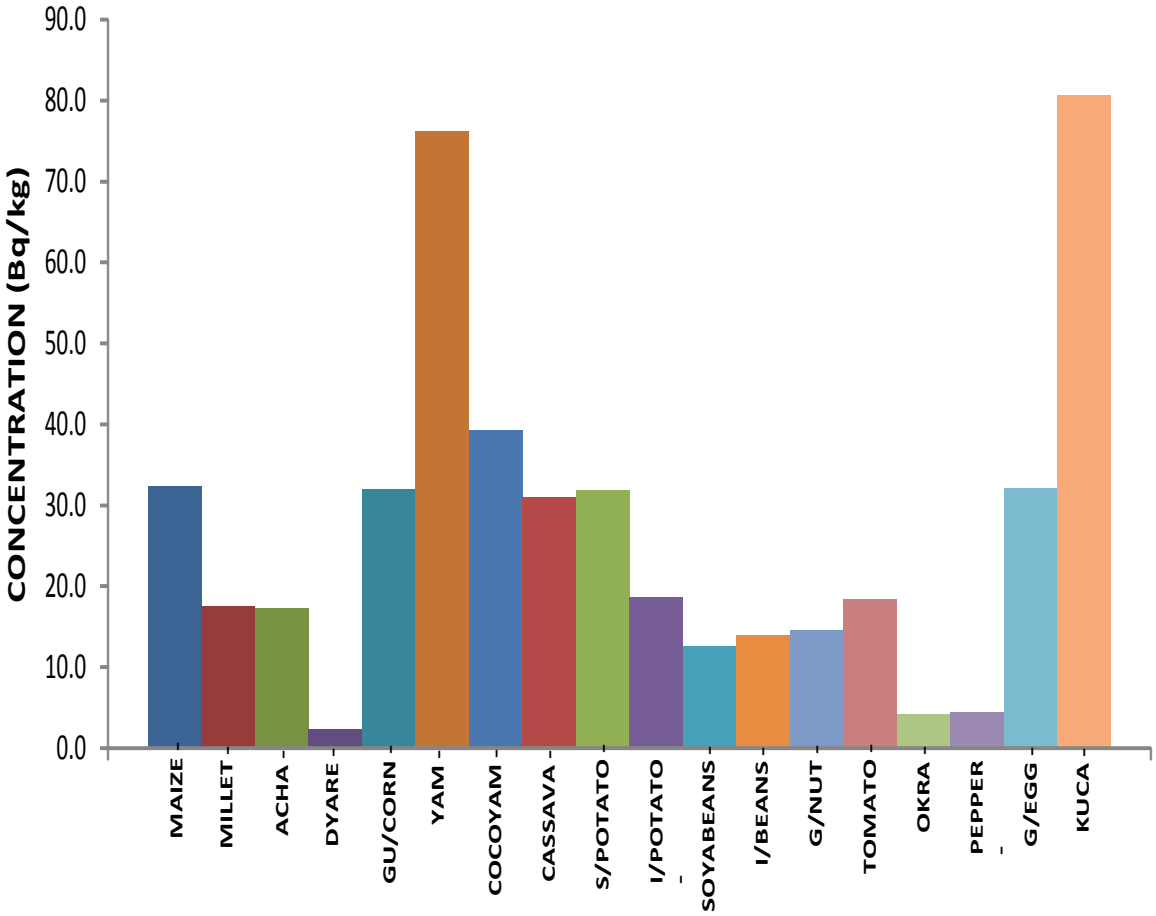


Figure 5.2: Distribution of ^{226}Ra in food crop samples from parts of Jos.

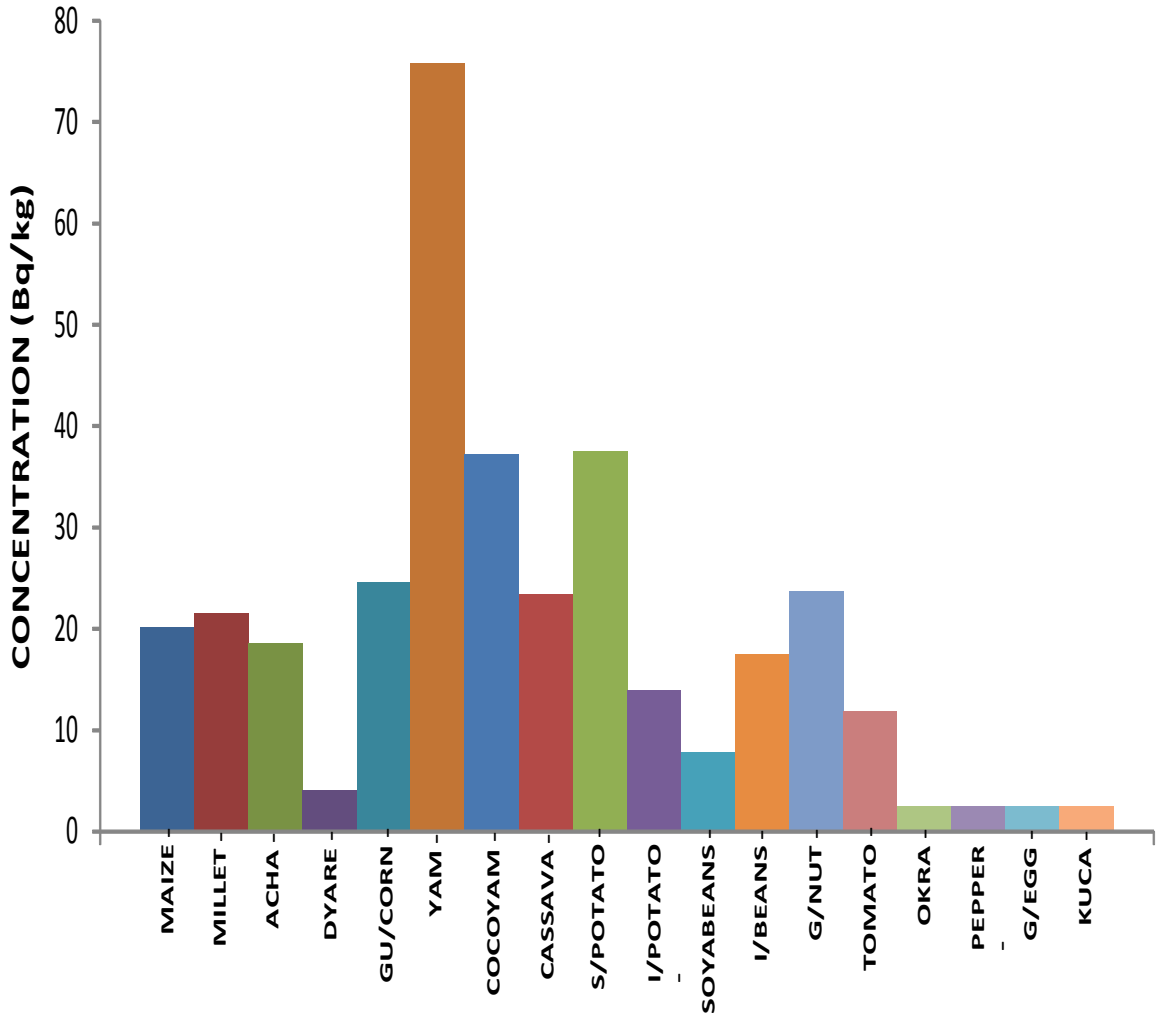


Figure 5.3: Distribution of ^{232}Th in food crop samples from parts of Jos.

the value for yam (75.8Bq/kg) in the present study, while the values of 181.5 Bq/kg for ^{40}K and 5.42 Bq/kg for ^{226}Ra were lower than the values of 602.1 Bq/kg for ^{40}K and 76.2 Bq/kg for ^{226}Ra in the present study. The range of values of 10.6 to 46.4Bqkg^{-1}for ^{40}K, 0.5 to 2.7 Bqkg^{-1}for ^{226}Ra and BDL to1.4 Bqkg^{-1}for ^{232}Th reported by Olomo (1990) in tuber from Nigeria are observed to be lower than the range of values obtained in the present work.

5.1.3 Activity concentrations in tuberous vegetables

From the two tuberous vegetables analyzed, it could be seen from Table 4.1 that the activity concentrations of ^{40}K activity concentration value of 508.2 Bq/kg obtained in Irish potatoes was higher than 389.1 Bq/kg in sweet potatoes. Further more the activity concentration of ^{226}Ra and ^{232}Th were respectively higher in sweet potato than Irish potatoes. The ^{40}K concentration obtained in the present study for sweet potatoes (389.1 Bq/kg) and Irish potatoes (508.2 Bq/kg) are higher than those reported by Hernandez et al., (2004), where 136 Bq/kg for sweet potato and 74Bq/kg for Irish potato were obtained. The activity concentrations found in potatoes from India in 1982 where the values were 166.7 Bq/kg for ^{40}K, 0.2 Bq/kg for ^{226}Ra and 0.28 Bq/kg for ^{232}Th (Ramachandran and Mishra, 1989) were lower by a factor of about three than the values obtained for Irish potatoes in the present study. The activity concentration of 4.5Bq/kg for ^{226}Ra in potatoes from Iran reported by Samavat et al., (2006) is about eight times lower in magnitude than the value of 37.5Bq/kg for sweet potatoes from the study areas. In Egypt, the ^{40}K concentration value of 63Bq/kg in sweet potatoes reported by Badran et al., (2003) was about six times lower in magnitude than the value obtained in the study.

5.1.4 Activity concentrations in legume food crops

In the legume food crops presented in Table 4.1, ^{40}K activity concentration value of 534.3 Bqkg^{-1} was the highest in soya beans, local beans has activity concentration of 444.1 Bq/kg and the lowest activity concentration value of 296.8 Bqkg^{-1} was obtained in groundnut. Groundnut has the highest ^{226}Ra and ^{232}Th activity concentration values of 14.6 Bq/kg and 23.7 Bq/kg respectively followed by local beans with activity concentration value of 13.9 Bq/kg and 17.5 Bqkg^{-1} respectively. The lowest activity concentrations of ^{226}Ra and ^{232}Th in soya beans were 12.6 Bqkg^{-1} and 7.8 Bqkg^{-1} respectively. In the work reported by Hernandez, et al., (2004), where the activity concentration values were 380 Bq/kg, <2.10Bq/kg and 0.23 Bq/kg for ^{40}K, ^{226}Ra and ^{232}Th respectively in the locally

produced beans from Tenerife, Spain were significantly lower than the values obtained in the study. For instance, the ^{40}K concentration in the beans is about 64 Bq/kg smaller than the value obtained from Jos.

5.1.5 Activity concentrations in general vegetable

In the general vegetable presented in Table 4.1, tomato has the highest concentrations of ^{40}K and ^{232}Th with values 333.3 Bq/kg and 11.9 $Bqkg^{-1}$ respectively while the lowest activity concentrations of ^{40}K and ^{232}Th were obtained in garden-egg. ^{226}Ra has the highest concentration value of 32.1 $Bqkg^{-1}$ in garden-egg and ^{226}Ra was below detection limit (BDL) in okra. ^{232}Th was below detection limit (BDL) in okra, pepper and garden egg but tomatoes indicated significant ^{232}Th concentration value of 11.9 Bq/kg. In the leafy vegetable (Kuca) ^{232}Th was below detection (BDL) but ^{226}Ra and ^{40}K were detected with significant concentration values of 10.4 $Bqkg^{-1}$ and 80.6 respectively. In south west India, the radioactivity values of 71.92 $Bqkg^{-1}$, 0.064 $Bqkg^{-1}$ and 0.17 $Bqkg^{-1}$ for ^{40}K, ^{226}Ra and ^{232}Th respectively reported by India (Shanthi et al., 2009) were low when compared with the values obtained in this study. In Cameroon, the activity concentration values of 302 Bq/kg for ^{40}K and 42 Bq/kg for ^{226}Ra reported by Makon et al., (2011) in Vernonia vegetable were about four times higher in magnitude than the values of 80.6 Bq/kg for ^{40}K and 10.4Bq/kg for ^{226}Ra obtained in Kuca vegetable from Jos. While ^{232}Th concentration was below detection limit (BDL) in Kuca, the value in Vernonia vegetable was 17 Bq/kg. The activity concentrations in Ugwu (Telfairia) vegetable from Ondo southwestern Nigeria were 721.6 Bq/kg for ^{40}K, 28.94 Bq/kg for ^{238}U and 8.54 Bq/kg for ^{232}Th (Eyebiokin et al., 2005). These values were higher than values in Kuca in Jos.

5.2 Activity concentrations in food crops from Abeokuta

5.2.1 Activity concentrations in cereal food crops

Figures 5.4, 5.5 and 5.6 are the histograms that illustrated the mean activity concentrations distribution in all the food crops from Abeokuta. From Table 4.2, the mean activity concentrations of all the three radionuclides (^{40}K, ^{226}Ra and ^{232}Th) in maize from Abeokuta were higher than the activity concentrations in rice from the same area. The ^{40}K, ^{226}Ra and ^{232}Th concentrations of 341.9 Bq/kg, 33.3 Bq/kg and 9.2 Bq/kg respectively were obtained in maize while 215.1 Bq/kg, 27.6 Bq/kg and 6.0 Bq/kg respectively were measured in rice. In the work carried out by Bolca et al., (2007), ^{40}K was observed to be

almost doubled the value of 239.6 Bq/kg in the study for maize and the concentration of 25.82 Bq/kg for ^{226}Ra was slightly lower than the value of 32.3 Bq/kg in the study. Mlwilo et al., (2007) reported 24.67 Bq/kg for ^{40}K, 5.02 Bq/kg for ^{238}U and 3.82 Bq/kg for ^{232}Th in rice from Tanzania. These values were lower than the values obtained in the study.

5.2.2 Activity concentrations in tuber food crops

The highest ^{40}K activity concentration value of 1048.1 Bq/kg was obtained in tuber yam while the lowest value of 587.4 Bq/kg was obtained in cassava. The ^{226}Ra activity concentration value of 37.3 Bq/kg was measured in cocoyam while yam and cassava have approximate activity concentration value of 32.0 Bq/kg each. Cassava has the highest ^{232}Th activity concentration value of 28.3 Bq/kg while the lowest value of 6.1 Bq/kg was obtained in cocoyam. While the radionuclide levels of 104.77 Bq/kg for ^{40}K and 4.71Bq/kg for ^{232}Th in cassava from Ile-Ife (Arogunjo et al., 2005) were lower than the corresponding concentration values in cassava from Abeokuta, the activity concentrations of the radionuclides varied from 10.6 to 46.4 Bq/kg for ^{40}K, 0.5 to 2.7 Bq/kg for ^{238}U and 36.4 to 186.9 Bq/kg ^{232}Th in tuber products (Akinloye and Olomo, 2000) were low compared to the range of values in tuber from Abeokuta.

5.3 Comparison of activity concentrations in common food crops from the two areas of study

The common food crops from Jos and Abeokuta were maize, yam, cocoyam and cassava (Table 4.3). All the tuber food samples from Abeokuta indicated higher ^{40}K activity concentration than the corresponding tuber food samples from Jos. The ^{40}K mean activity concentration was higher by a factor of about 4.7 in maize from Jos than Abeokuta while ^{232}Th mean activity concentration in maize from Abeokuta was about one-half of the mean activity concentration in maize from Jos. The ^{226}Ra mean activity concentration was almost the same. The ^{40}K mean concentration was higher by a factor of about 0.7 in yam from Abeokuta than Jos; while ^{232}Th mean activity concentration in yam was about seven times higher in Jos than Abeokuta. ^{226}Ra activity concentration was more than double in yam from Jos than Abeokuta. Cocoyam was higher in ^{40}K activity concentration by a factor of 0.3 in Abeokuta than Jos while ^{232}Th activity concentration in cocoyam was over five times higher in Jos than Abeokuta and ^{226}Ra activity concentrations were very close in the cocoyam from the two areas.

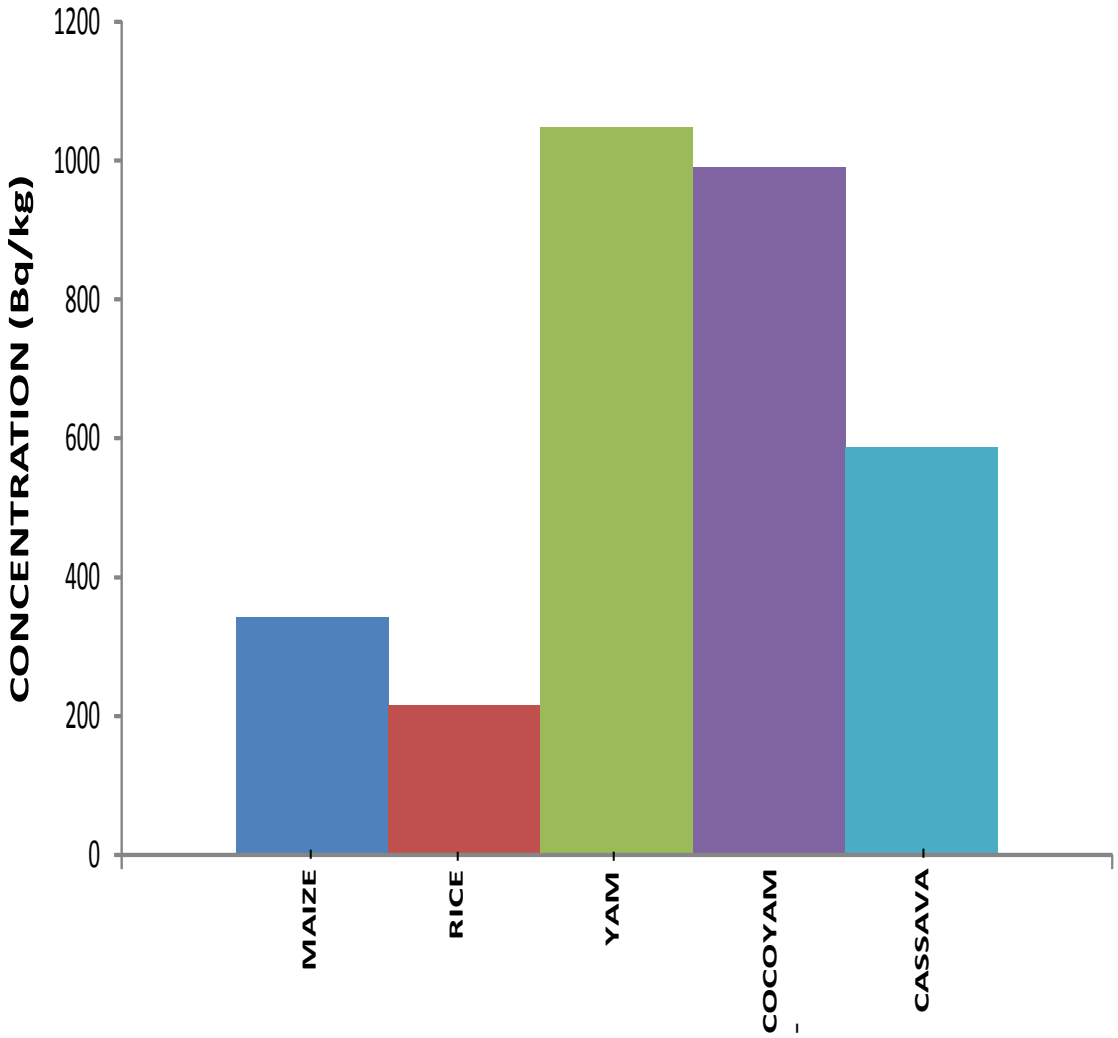


Figure 5.4: Distribution of ^{40}K in food crop samples from parts of Abeokuta.

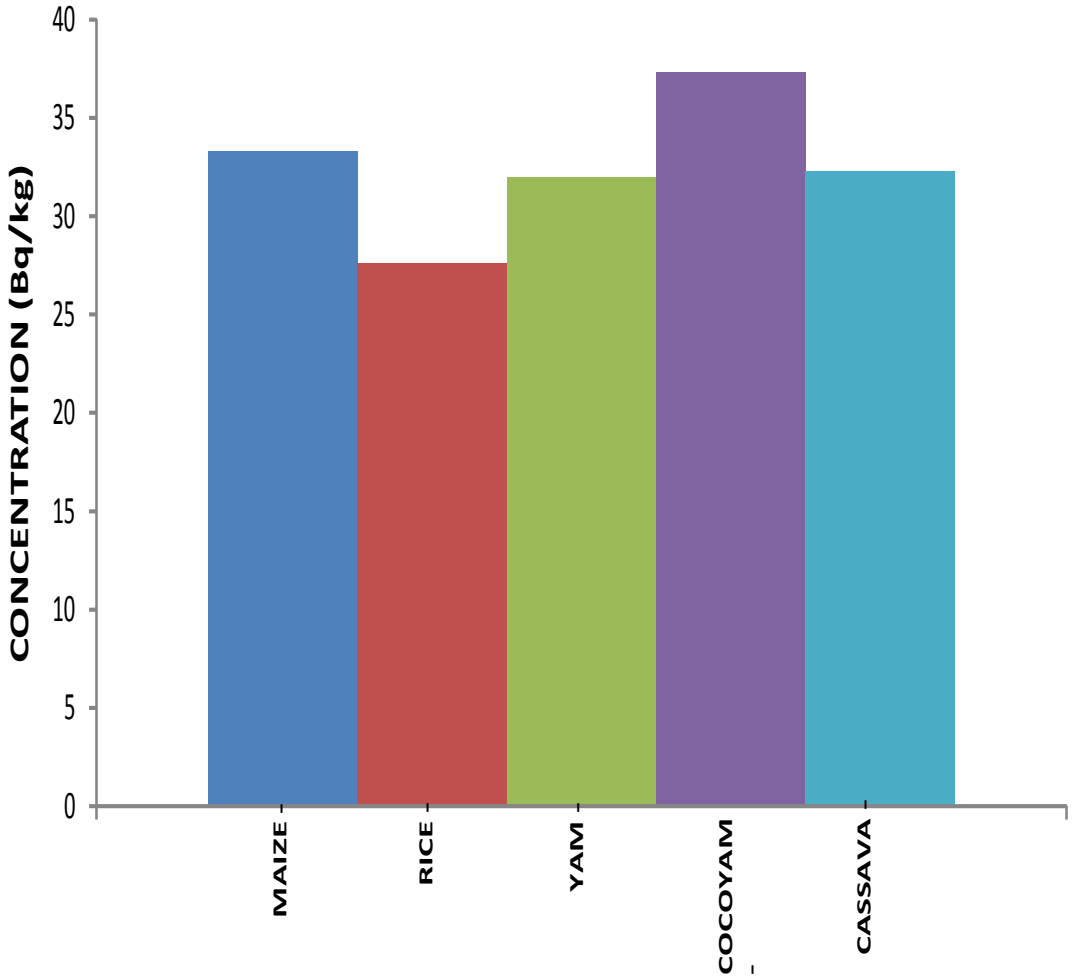


Figure 5.5: Distribution of ^{226}Ra in food crop samples from parts of Abeokuta.

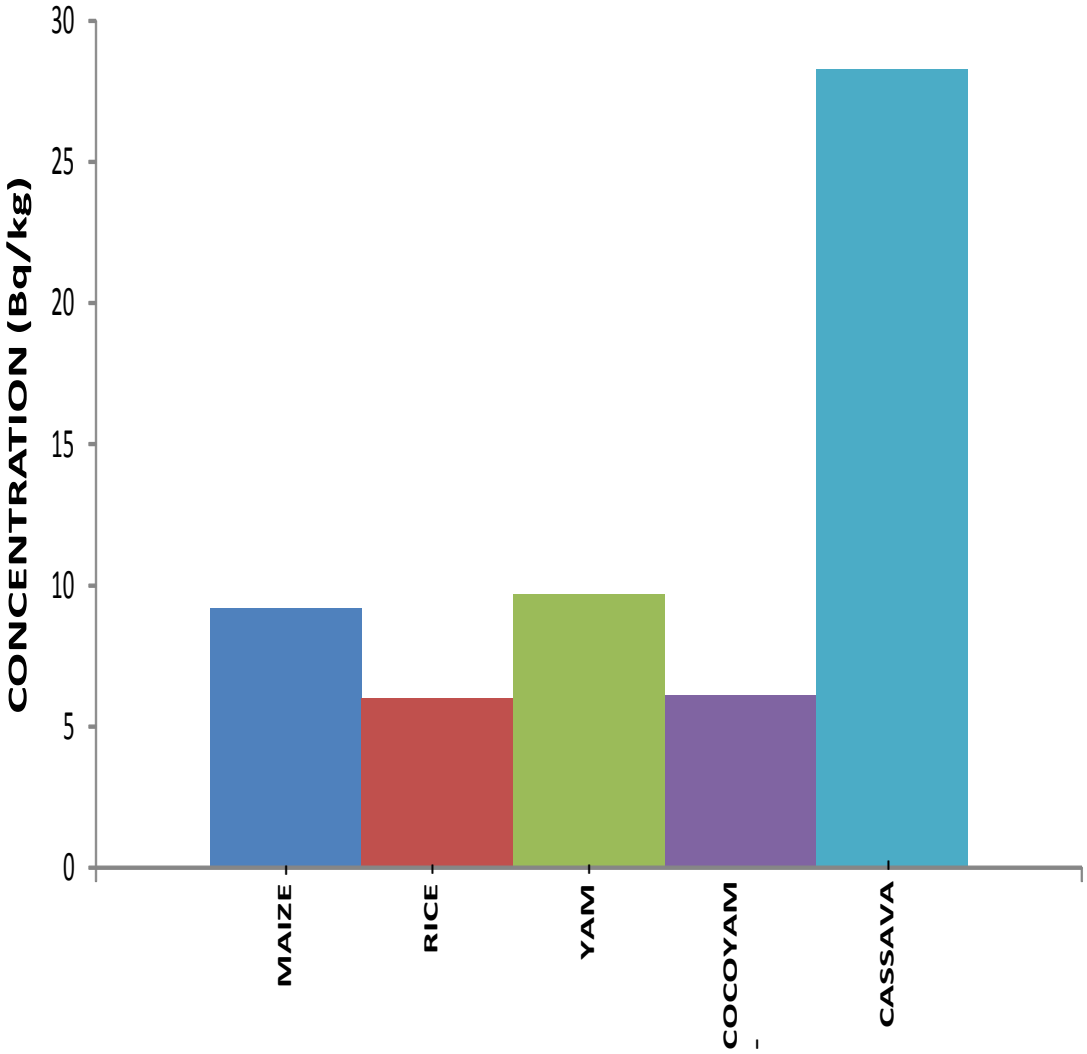


Figure 5.6: Distribution of ^{232}Th in food crop samples from parts of Abeokuta.

^{40}K and ^{232}Th activity concentrations in cassava were higher by a factor of over 0.2 each in Abeokuta than Jos; and the ^{226}Ra activity concentrations were very close. Except in cassava where ^{232}Th activity concentration was higher in Abeokuta than Jos (Table 4.3), the ^{232}Th concentration levels in maize, yam and cocoyam were higher in Jos than Abeokuta. Although ^{40}K activity concentration levels in yam, cocoyam and cassava were higher in the common food crops from Abeokuta than Jos, on the average, the activity concentrations of the three radionuclides (^{40}K, ^{226}Ra and ^{232}Th) in the common food crops were higher in Jos than Abeokuta.

The similarity and variations in radioactivity levels in the food crops analyzed in the study depend on the different rate of radionuclides uptake by different food species which is characterized by the distribution of the radionuclides in the soil (earth crust) depending on the geographical and geological setting of a location.

5.4 Comparison of activity concentrations in food crops with other countries

Radioactivity measurements in different food samples have been carried out and reported in many countries of the world. The results obtained in the study are comparable to the values reported in other countries including high background radiation areas. As shown in Table 5.1, the activity concentration of ^{232}Th in rice was six times higher in India than the value obtained in the present study while the activity concentration of ^{40}K in the rice from India was one-half of the value obtained in the study. Except for the activity concentration of ^{40}K in beans from India that was relatively high compared to the value obtained in the study, the activity concentration values of ^{226}Ra, ^{232}Th and ^{40}K in beans from other countries were lower than the values obtained in the present study. The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in potatoes from India and Iran were low compared to the values obtained in the present study. While the activity concentration of ^{40}K in yam was about four times higher in the present study than the values reported in India, the activity concentration of ^{232}Th was about three times higher in India than the values obtained in the study. The activity concentration of ^{40}K in maize reported in Turkey was about double the value obtained in the study while the values obtained for ^{226}Ra and ^{232}Th in maize were low in other countries compared to the values in the study. While the activity concentration of ^{40}K in the vegetables was higher in the study than the values from other countries, the activity concentration of ^{226}Ra in vegetable from Tanzania was significantly higher than the values obtained in the present study. The activity concentration values of the three radionuclides in the vegetables from Cameroon were relatively high compared to the values obtained in the study.

Table 5.1: Comparison of activity concentrations of radionuclides (Bq/kg) in foodstuffs in the present study with other countries

Food Type	^{226}Ra	^{232}Th	^{40}K	Country
Rice	5.02	3.82	24.67	Tanzania
Rice	0.37	-	-	Iran
Rice	3.07	34.3	120.8	India
Rice	27.6	6.0	215.1	***Present study***
Beans	-	-	73.5	Lebanon
Beans	1.26	1.31	650.00	India
Beans	<1.23	<0.62	380.00	Spain
Red Beans	9.74	3.5	257.0	Nigeria
Local beans	13.9	17.5	444.1	***Present study***
Soya beans	12.6	7.8	534.3	***Present study***
Potatoes	0.20	0.28	166.7	India
Potatoes	<0.44	<0.20	74.0	Spain
Potatoes	-	-	96.0	Egypt
Potatoes	4.5	-	-	Iran
Sweet potatoes	-	-	63	Egypt
Sweet potatoes	<1.68	<0.63	136	Spain
Potatoes	-	-	84.7	Lebanon
Sweet potato	31.8	37.5	389.1	***Present study***
Irish potato	18.6	13.9	508.2	***Present study***
Tuber (Tapioca)	5.42	107.0	181.1	India
Yam	39.3	37.2	754.4	***Present study***

Table 5.1: Continues

Food Type	^{226}Ra	^{232}Th	^{40}K	Country
Cereal	-	-	45.1	Lebanon
Wheat	0.12	0.25	150.8	India
Maize	13.23	4.08	48.79	Tanzania
Maize	25.82	-	491.62	Turkey
Maize	32.3	20.2	239.6	***Present study***
Maize	33.3	9.20	341.9	***Present study***
Vegetables	393.0	-	-	Tanzania
Vegetables	-	-	63.8	Lebanon
Vegetable	42	17	302	Cameroon
Okra	BDL	BDL	213.0	***Present study***
Perpper	4.5	BDL	132.4	***Present study***
Garden-egg	32.1	BDL	122.3	***Present study***
Tomatoes	-	-	63.0	Egypt
Tomatoes	4.5	-	-	Iran
Tomatoes	<0.57	<0.24	57.0	Spain
Tomatoes	0.064	0.17	71.92	India
Tomatoes	18.4	11.9	333.3	***Present study***
Mushroom	-	-	92.0	Japan

Generally the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in different foodstuffs in the present study were observed to be higher than the reported values for the same foodstuffs in other countries. This observation was in agreement with that of Arogunjo et al., (2009) that concentrations of the radionuclides in Jos were higher than that reported in other countries and even in countries with high natural background radiation.

5.5 Activity concentrations of radionuclides in farm soil samples

As illustrated in the table 4.4, the mean activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Jos-Plateau area comprising the three mining sites (Bitsichi, Bukuru and Ropp) varied from 109 ± 28 Bq kg^{-1} (Bukuru) to 163 ± 92 Bq kg^{-1} (Bitsichi), 154 ± 56 Bq kg^{-1} (Bukuru) to 451 ± 368 Bq kg^{-1} (Bitsichi) and 466 ± 221 Bq kg^{-1} (Bitsichi) to 1062 ± 199 Bq kg^{-1} (Ropp), respectively. In Abeokuta, the mean activity concentrations obtained were 65 ± 29 Bq kg^{-1}, 184 ± 205 Bq kg^{-1} and 411 ± 341 Bq kg^{-1} for ^{226}Ra, ^{228}Th and ^{40}K, respectively. Except for ^{40}K, the activity concentrations of other radionuclides were relatively high in Bitsitchi when compared with activity concentration values in Ropp and Bukuru in the same north-central zone and, Abeokuta in the south western zone of Nigeria as illustrated in Figures 5.7, 5.8 and 5.9. Generally, the activity concentration values obtained for Ropp and Bukuru were observed to be very similar. This may be attributed to the same geological formations in Jos-Plateau. The relatively high values recorded in Bitsitchi when compared with those in Ropp and Bukuru may be attributed to the variations in the environment resulting from past decades of mining activities. Tin tailings from the area have been found to contain very high concentrations of ^{232}Th and ^{238}U, averagely between 16.8×10^2 and 72.2×10^3 Bq kg^{-1} respectively (Oresegun and Babalola, 1990, 1993, Ademola, 2008a). This observation was similar to Mustapha et al., (2007) that reported activity concentration of 1630Bqkg^{-1}, 7060 Bqkg^{-1} and 1750Bqkg^{-1} for ^{40}K ^{226}Ra and ^{232}Th respectively in the col-tan from a mining site in eastern Democratic Republic of Congo.

The concentration of ^{232}Th in the col-tan was about five times higher in magnitude than corresponding result from farm soils in the Bisichi. Also the ^{226}Ra concentration was about fifty times higher than the corresponding result in the farm soils from Bisichi. The results suggest that col-tan or tin-tailings are very rich in radionuclides compared to that in soils.

The radioactivity levels in soils in some countries are lower than the values obtained in the study. For instance the activity concentrations in the soils of Niab Faisalabad, Pakistan were 30.5 Bq $kg^{-1}$for ^{226}Ra and 55.8 Bq kg^{-1} for ^{232}Th (Akhtar et al., 2004) while in the soils of Bangalore region, India, the activity concentrations were

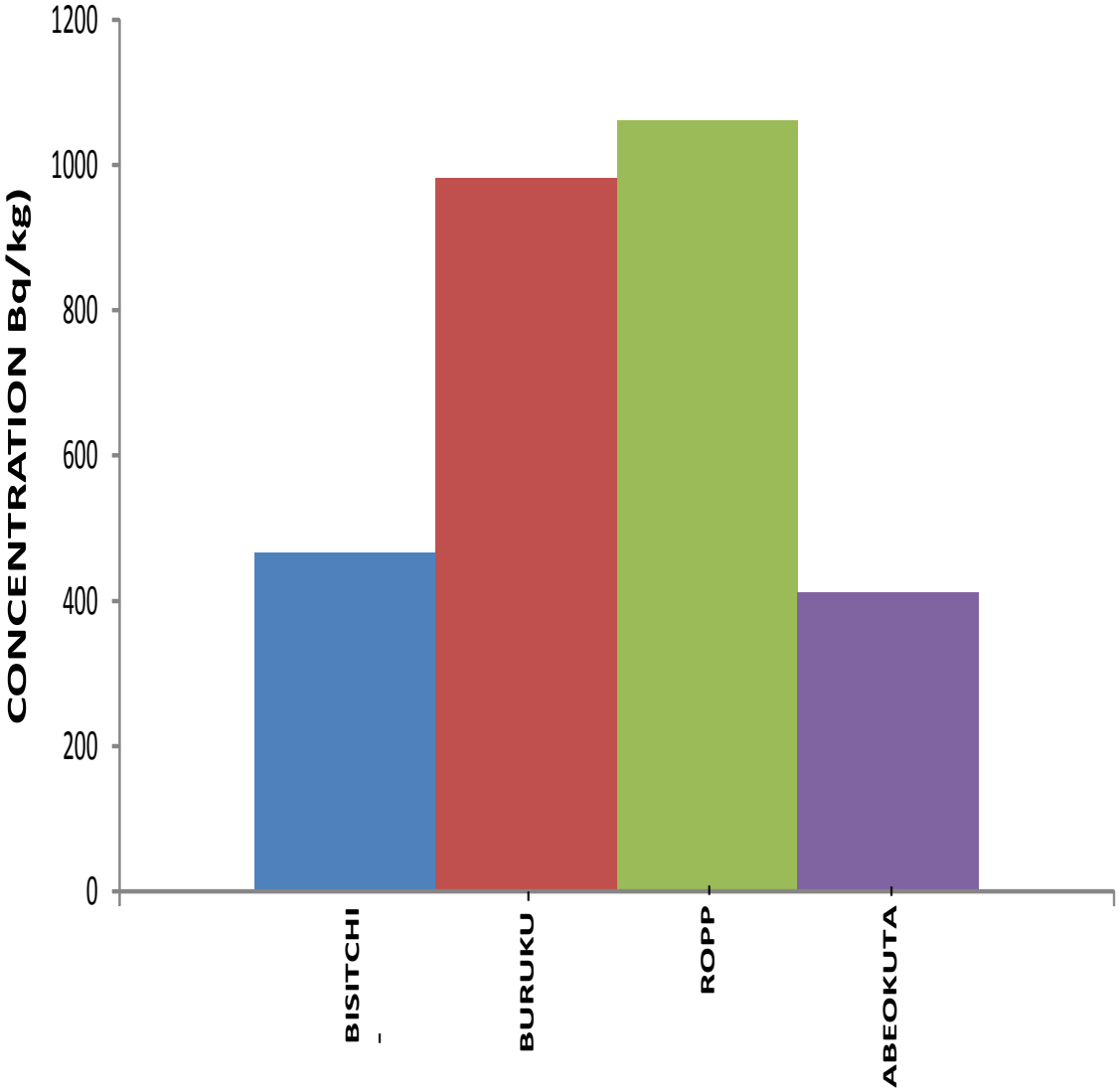


Figure 5.7 Distribution of ^{40}K in the farm soil samples from the two study areas.

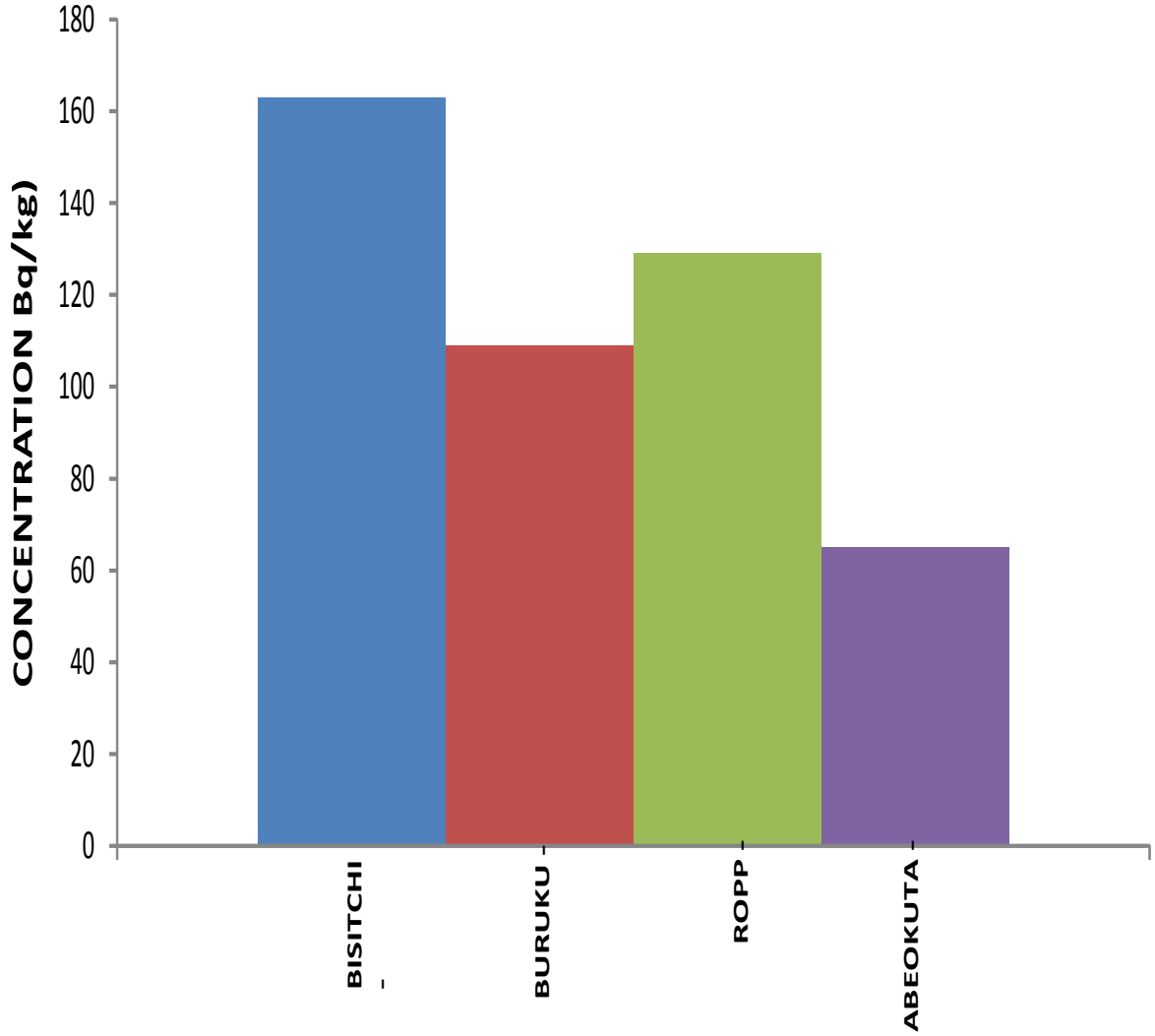


Figure 5.8: Distribution of ^{226}Ra in the farm soil samples from the two study areas.

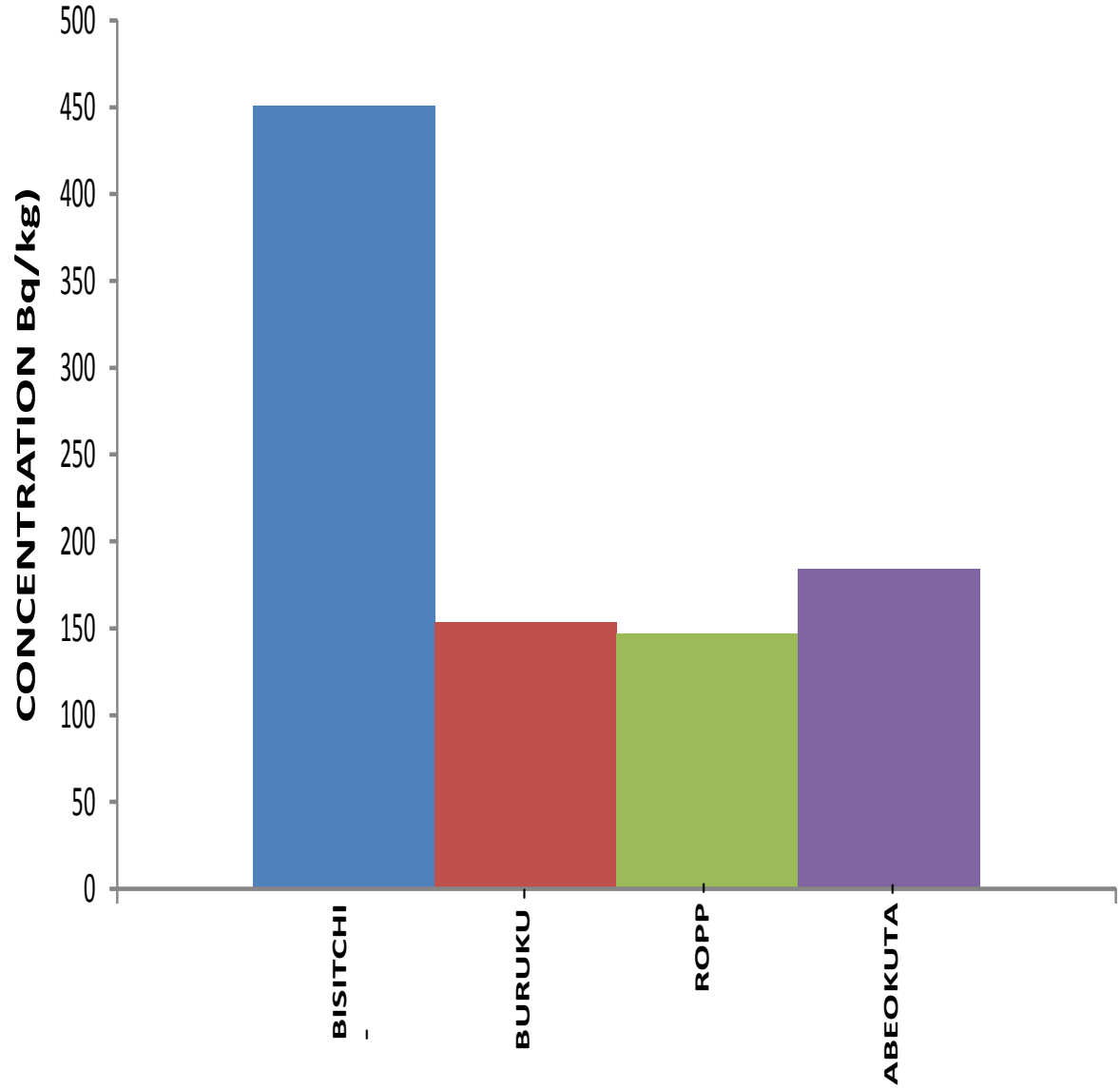


Figure 5.9: Distribution of ^{232}Th in the farm soil samples from the two study areas

635 Bq kg^{-1} for ^{40}K, 26.2 Bq kg^{-1} for ^{226}Ra and 53.1 Bq kg^{-1} for ^{232}Th (Shiva, et al., 2008). The activity concentrations in the soils of few areas in Nigeria were reported as 222 Bq kg^{-1} for ^{40}K, 39 Bq kg^{-1} for ^{226}Ra and 75 Bq kg^{-1} (Farai and Jibiri, 2000); 355 Bq kg^{-1} for ^{40}K, 31 Bq kg^{-1} for ^{226}Ra and 63 Bq $kg^{-1}$for ^{232}Th (Arogunjo et al., 2002); 219.8 Bq $kg^{-1}$for ^{40}K, 20.3 Bq $kg^{-1}$for ^{226}Ra and 21.1 Bq kg^{-1} for ^{232}Th (Jibiri and Bankole, 2006) and 261.37Bq/kg for ^{40}K, 50.01 Bq/kg for ^{238}U and 84.6 Bq/kg (Egunyinka, et al., 2009). The activity concentrations in the soils from Mrima Hill, Kenya were 805.38 Bq kg^{-1} for ^{40}K, 207.03 Bq kg^{-1} for ^{226}Ra and 500.7 Bq kg^{-1} for ^{232}Th (Kebwaro et al., 2011). These results of radioactivity levels in soils from Kenya were higher than the values obtained in the present study.

5.6 Effective dose due to ingestion of foodstuff

As seen from Table 4.6, the estimated total effective dose due to intake of radionuclides varied from 0.2 µSv y^{-1} in local beans, up to 1852.0 µSv y^{-1} in yam from Jos. The tuber food crops were found to deliver more dose than the other food crop types. In Table 4.7 it is shown that cassava which is a popular staple food in Abeokuta and its environs has highest effective dose value of 1064.6 µSv y^{-1} among the tuber food samples. The two cereal crops (maize and rice) consider in the study have very close mean effective doses of 118.5 µSv y^{-1} and 104.7 µSv y^{-1} while cocoyam has the least effective dose value of 56.7 µSv y^{-1}.

The expected radiological effects due to ingestion of the food crops on the populace in the study areas depend directly on the reality of dietary habits and the food choices. Cereal food crops which constitute the major food types of nutritive importance in Jos and its environs were significantly low in activity concentrations of ^{40}K, ^{226}Ra and ^{232}Th and the resulting effective doses were relatively low too.

5.7 Absorbed and Effective Doses in Farm Soils

As shown in Table 4.8, the mean absorbed dose rates (nGy h^{-1}) in air at 1 m above the ground determined in farm soils at each study area does not directly give the radiological health hazard to which an individual is exposed. However Bisitchi has the highest mean absorbed dose rate of 350±270 nGy/h while Abeokuta recorded the least as 167±140 nGy/h. These values are 2-5 times greater than world average value of 59 nGy h^{-1} (UNSCEAR, 2000). The effective dose rate was 0.24±0.08 mSv y^{-1} at Bukuru, and Ropp,

0.43±0.33 mSv y^{-1} at Bitsichi while a value of 0.21±0.18 mSv y^{-1} was obtained in Abeokuta.

From a radiological point of view, the doses obtained on the local population from the farm

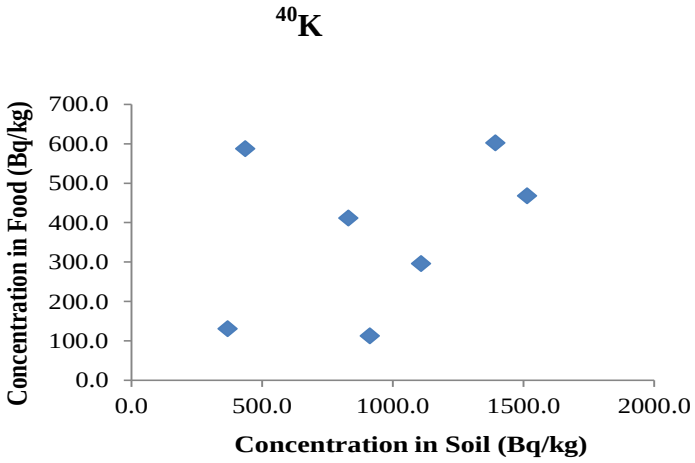
soils in Bukuru, Ropp and Abeokuta are low while in Bisichi the dose level is slightly higher than the world average effective dose to individuals from soil (0.30 mSv y^{-1}) (Ademola, 2008a). Therefore the radiological health burden due to the farm soils is expected to be more pronounced in Bisichi than any other area in the study.

5.8 Cancer risks due ingestion of food crops and radiation exposure from farm soils

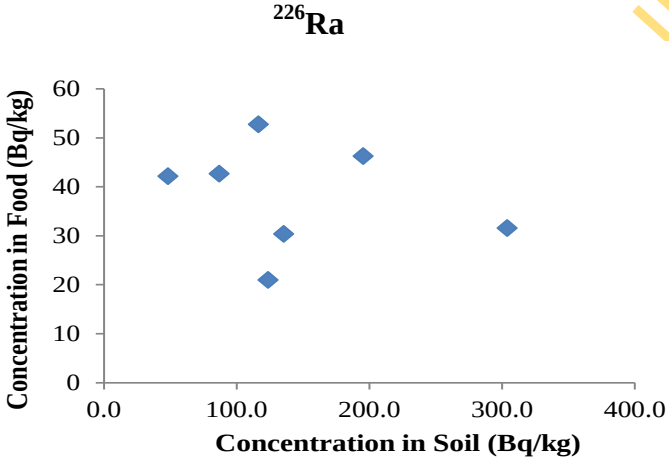
As shown Tables 4.9 and 4.10, the cancer risks due to ingestion of ^{226}Ra, ^{232}Th and ^{40}K radionuclides vary from 2.34 x 10^{-7} (dyare) to 4.3 x 10^{-3} (yam) in Jos and 2.82 x 10^{-4} (cocoyam) to 3.80 x 10^{-3} (cassava) in Abeokuta. The total cancer risk for intake of all the food crops from Jos was 1.28 x10^{-2} while from Abeokuta the risk was 8.32 x 10^{-3}. As shown in Table 4.11, the total cancer risk due to radiation exposure from the farm lands in Jos was 8.75x10^{-4} and 2.51 x10^{-4} was obtained in Abeokuta. Using equation 4.8, the sum of cancer risks due to radiation exposure from farm soil and food ingestion were obtained as 1.42 x10^{-2} and 0.86 x10^{-2} for Jos and Abeokuta respectively. These values are slightly higher than the world average value of 1.0 x 10^{-3}.Therefore the cancer risks due to the ingestion of food crops and the radiation exposure from farm soils are high in the study areas.

5.9 Transfer factor of radionuclides from soil-to-food crops

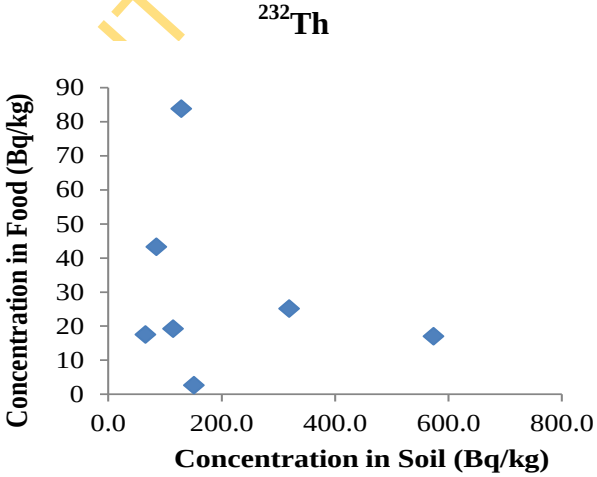
The relationships between the activity concentrations of the radionuclides in the food crops and in the soil samples are shown in Figures 5.10, 5.11, 5.12 and 5.13 for Guinea corn, maize, yam and cassava respectively. From these figures transfer factors, TFs for ^{40}K, ^{226}Ra and ^{232}Th were obtained and the result is summarised in Table 5.2. From Table 5.2, it could be seen that TFs of ^{232}Th in all the food crops are smaller than the values obtained for ^{226}Ra. This may be attributed to high solubility



(a)



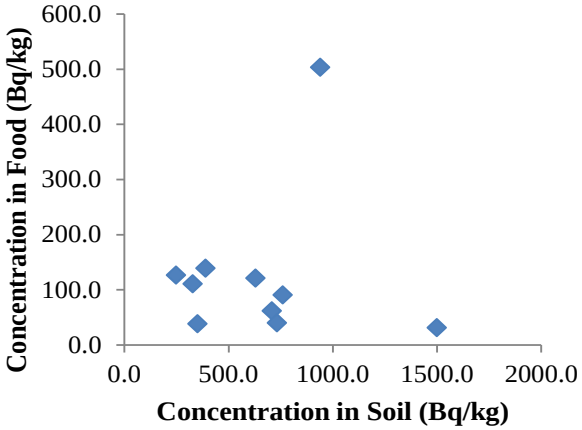
(b)



(c)

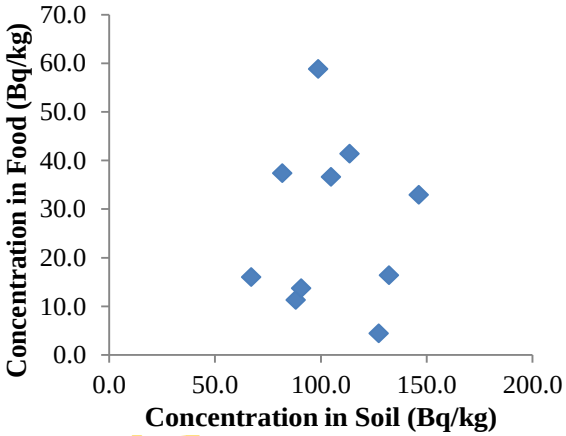
Figure 5.10: Relationships between activity concentrations of radionuclides in Guinea corn and soil.

^{40}K

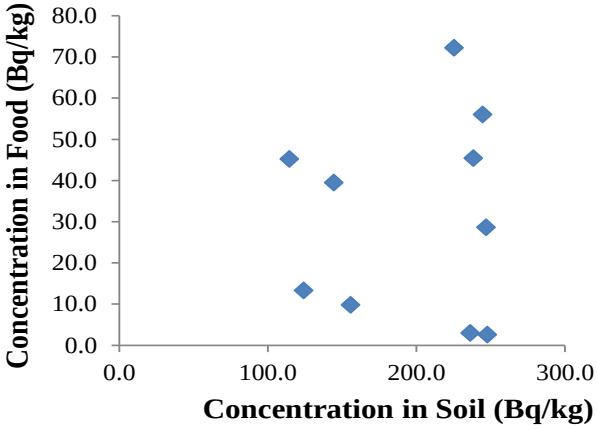


(a)

^{226}Ra



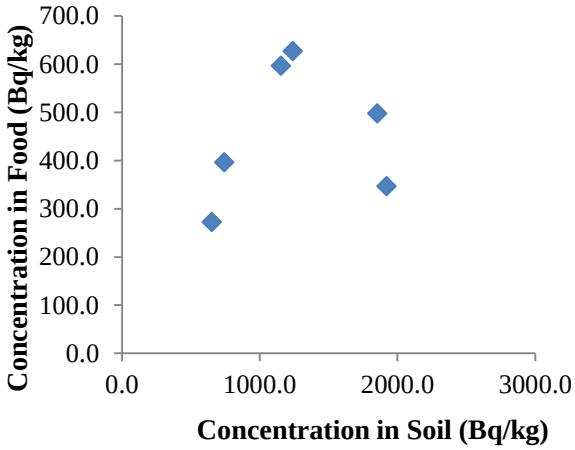
^{232}Th



(c)

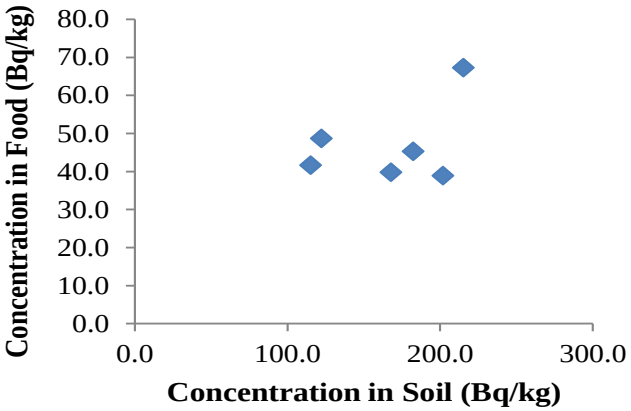
Figure 5.11: Relationships between activity concentrations of radionuclides in maize and soil.

^{40}K



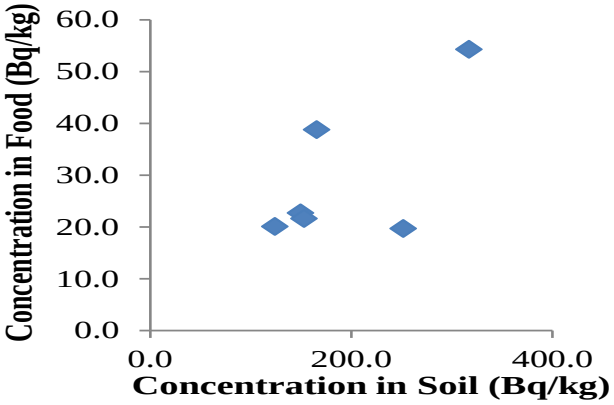
(a)

^{226}Ra



(b)

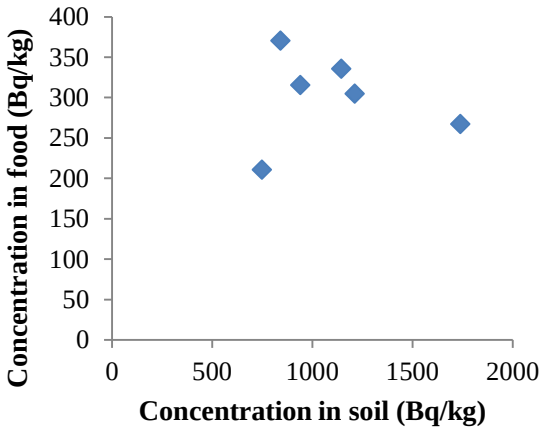
^{232}Th



(c)

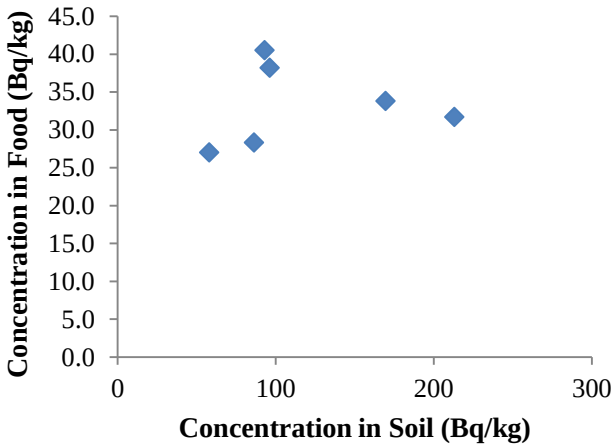
Figure 5.12: Relationships between activity concentrations of radionuclides in yam and soil.

^{40}K



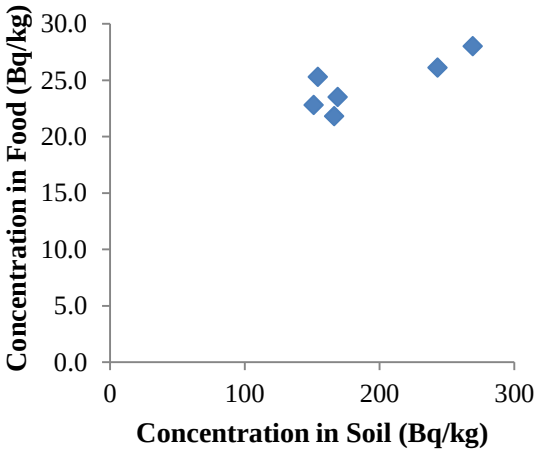
(a)

^{226}Ra



(b)

^{232}Th



(c)

Figure 4.13: Relationships between activity concentrations of radionuclides in cassava and soil.

Table 5.2: Transfer factors of the radionuclides.

Food Type	TF ($^{40}_{K}$)	TF ($^{226}_{Ra}$)	TF ($^{232}_{Th}$)
Guinea corn	$3.6x10^{-1}$	$2.0\ x10^{-1}$	$7.0\ x10^{-2}$
Maize	$1.6\ x10^{-1}$	$2.4\ x10^{-1}$	$1.5\ x10^{-1}$
Yam	$3.2\ x10^{-1}$	$2.7\ x10^{-1}$	$1.5\ x10^{-1}$
Cassava	$2.5\ x10^{-1}$	$2.3\ x10^{-1}$	$1.2\ x10^{-1}$

characteristics of ^{226}Ra compared to ^{232}Th. This observation is in agreement with the reports from Martinez-Aguirre et al., (1995) and Chen et al., (2005). Except in Guinea corn, the TFs of radionuclides for other food crops were about ten times higher than the reported values in different food crops in other studies (Uchida and Tagami, 2007; Benttecourt et al., 1988; Frissel and Koster, 1988; Shanthi et al., 2001). Chen (2005) reported that soil-to-maize (shoot) transfer factor as 0.0074 and soil-to-maize (root) as 0.081 for ^{226}Ra; 0.0061 soil-to-maize shoot as 0.00045 and soil-to-maize (root) as 0.0061 for ^{232}Th. These values are remarkably lower than the results obtained for soil-to- maize and Guinea corn (cereals) for ^{226}Ra and ^{232}Th in the present work. This may be attributed that only the grains were considered and from literature radionuclide accumulation are more at shoot than the grains. According to Chen et al., (2005), accumulation of radionuclides in plants is higher in roots than shoots and higher in shoots than grains. Tubers were found to exhibit higher transfer factors (TFs) than the cereals. Generally the results indicated that the uptake of the radionuclides from the soil was crop-specific and the variation in transfer factor, TF may be attributed to different characteristic of the food crops and concentration of radionuclides in the soils (Tome, 2003). The extent to which these factors affected the TFs were not determined in this study given the limitation stated earlier.

5.10 CONCLUSION

The activity concentrations of natural radionuclides ^{40}K, ^{226}Ra and ^{232}Th in the farm soil and food crops grown in parts of Jos and Abeokuta, have been measured using gamma-ray spectroscopy. Concentrations of the three radionuclides have been used to estimate the effective dose and cancer risks due to food ingestion. The absorbed dose, effective dose and cancer risks from external exposure due to farm soil radioactivity were also estimated. From the results obtained, the following conclusions are made:

1. The result from Jos showed that the mean concentration values of ^{226}Ra, ^{232}Th and ^{40}K in the food crops collected for the study, ranged from BDL-76.2 Bq/kg, BDL-75.8 Bq/kg and 67.8-754.4 Bq/kg respectively. The ^{226}Ra and ^{232}Th radionuclides showed almost the same values of activity concentrations in the common foodstuffs (yam and cocoyam) from Jos and Abeokuta.
2. The radionuclide with the highest activity concentration in each of the food samples collected from Jos and Abeokuta was ^{40}K. The concentration of ^{40}K was relatively higher in tubers than in cereal from the two study areas.

3. The ^{226}Ra and ^{232}Th activity concentrations in food crops were relatively higher in Jos than Abeokuta. The tin mining in Jos area appears to be the principal differential factor for the elevated radioactivity, otherwise the two areas could be considered to exhibit similar in natural radioactivity.

4. The activity concentration in each foodstuff in the present study was found to be higher when compared with the concentration of corresponding foodstuffs in other studies from other parts of the world, even the countries known for high background radiation.

5. The average values of ^{226}Ra, ^{232}Th and ^{40}K in farm soil from Jos ranged from 109 ± 28 to 163 ± 92 Bq kg^{-1}, 147 ± 75 to 451 ± 368 Bq kg^{-1} and 466 ± 221 to 1062 ± 199 Bq kg^{-1}, respectively. The mean activity concentrations obtained for ^{226}Ra, ^{232}Th and ^{40}K in farm soil from Abeokuta were 65 ± 29 Bq kg^{-1}, 184 ± 205 Bq kg^{-1} and 411 ± 341 Bq kg^{-1} respectively. The radioactivity levels in the soils from Jos and Abeokuta were similar.

6 The mean total absorbed gamma dose rates varied between 194 ± 59 nGy h^{-1}(Bukuru) and 350± 270 nGy h^{-1} (Bisichi) in Jos, whereas in Abeokuta it was 167 ± 140 nGy h^{-1}. These values are 2-5 times higher in magnitude than the world average of 59nGy^{-1} (UNSCEAR, 2000).

7. The average annual outdoor effective dose for the two areas were generally less than 1mSvy^{-1} except in some farms in Jos where values were as high as 2mSvy^{-1}. The extreme values in some of these locations were attributed to traces of tailings in the farm soils resulting from past mining activities.

8. The evaluated carcinogenic indexes were relatively higher in Jos than Abeokuta. Although the cancer risks due to ingestion of food crops from the two study areas were slightly higher than the world average of 1.0 x 10^{-3}. The consequence of higher activity values in food samples may lead to more internal radiological effects in Jos than Abeokuta. The radiological effects due to ingestion of the food crops in the areas may depend on the dietary habits and the food choices.

9. The transfer factors, TFs of radionuclides for Guinea corn, maize, yam and cassava from Jos were about ten times higher in magnitude than the reported values in different food crops in other studies. The study indicates that as much as 30% of the radionuclides in the soil could be transferred to the food crops.

5.11 Limitations and suggestions for further studies

The major constraint encounter in this work was lack of sufficient funds that would have facilitated transportation to remote villages and communities of the study areas. Another constraint was the inability to conclude the field works on time due to the continuous political crisis and hostility in Jos. These constraints affected and limited the number of locations covered for the study especially in Jos.

In view of these limitations and the experience gained in this study, the following suggestions are recommended for further studies:

(i) formal and proper introductions should be made to the community head and local people to enlighten them of the work, so that the safety of the researcher could be guaranteed while carrying out their work.

(ii) adequate financial and technical assistance is needed and the study should be expanded to determine the chromosomal conditions of the people in the two areas.

(iii) more rigorous studies should be carried out to link reported cancer cases in the area with calculations made in this work.

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APPENDIX 1

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Estimation of annual effective dose due to natural radioactive elements in ingestion of foodstuffs in tin mining area of Jos-Plateau, Nigeria

N.N. Jibiri [a,*], I.P. Farai [a], S.K. Alausa [b]

[a] *Radiation and Health Physics Research Laboratory, Department of Physics, University of Ibadan, Oyo State, Nigeria*
[b] *Department of Physics, Olabisi Onabanjo University Ago-Iwoye, Nigeria*

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Abstract

Soils and food crops from a former tin mining location in a high background radiation area on the Jos-Plateau, Nigeria were collected and analyzed by gamma spectrometry to measure their contents of ^{40}K, ^{238}U and ^{232}Th. As well as collecting samples, in situ dose rates on farms were measured using a precalibrated survey meter. Activity concentrations determined in food crops were compared with the local food derivatives or diets to investigate the possible removal or addition of radionuclides during food preparation by cooking or other means. Potassium-40 was found to contribute the highest activity in all the food products. The activity concentration of ^{40}K, ^{238}U and ^{232}Th in local prepared diets ranged between 60 and 494 Bq kg^{-1}, between BDL and 48 Bq kg^{-1} and between BDL and 17 Bq kg^{-1}, respectively. The internal effective dose to individuals from the consumption of the food types was estimated on the basis of the measured radionuclide contents in the food crops. It ranged between 0.2 μSv y^{-1} (beans) and 2164 μSv y^{-1} (yam) while the annual external gamma effective dose in the farms due to soil radioactivity ranged between 228 μSv and 4065 μSv.

Keywords: Radioactivity; Radionuclide; Food crops; Diet; Effective ingestion dose; Mining; Nigeria

* Corresponding author.
E-mail addresses: jibirinn@yahoo.com, nnamdi.jibiri@mail.ui.edu.ng (N.N. Jibiri).

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1. Introduction

Ingestion of radionuclides through food intake accounts for a substantial part of average radiation doses to various organs of the body and also represents one of the important pathways for long term health considerations (McDonald et al., 1999; Fernandez et al., 2004; Hernandez et al., 2004). The status of the soil on which food crops are grown will determine, to a significant extent, the quality of foodstuffs produced. An essential feature of soil is its ability to accumulate and retain over long periods radioactive isotopes introduced into the environment from external sources. Human dietary composition varies from place to place and from one individual to another. Natural radionuclides entering the food chain are mostly derived from the soil and, as a result, variation in soil radionuclide content is a prime source of geographic variability. Plant uptake also varies from species to species; hence the intake of different food products forms a secondary source of variability.

In Nigeria, the most important food basket of the country consists of grains and tubers (roots). These crops constitute a large percentage of the total diet for both low and medium income consumers in Nigeria. The major staples are yam, cassava, sorghum, maize, millet and rice. For instance, the consumption of rice represents about 9% of total calorie intake. Per capita consumption per annum of rice is about 24.8 kg (Olayemi, 1998; see also Table 5). While root crops are important foods in Nigeria, cereals account for one-half of calories consumed. Since food consumption is generally related to specific geographical locations as well as cultural, economic, social and even political conditions, food consumption and energy intake in the northern part of the country, where the present study is located, revolve largely around one food group: cereals. It has been found that cereals account for over 64% of the average daily energy intake and an average consumer has a daily intake of about 2393 kcal (Omosaiye, 2001; Maziya-Dixon et al., 2004).

In some parts of the world, population growth and movement, industrial development and food security have resulted in pressure to use agricultural lands containing relatively high levels of radioactivity, for instance in the monazite areas of India and Brazil, and in parts of Iran with ^{226}Ra anomalies where exposures up to tens of mSv, and in extreme cases 100 mSv, occur annually (UNSCEAR, 2000; Banzi et al., 2000). The area studied in the present investigation (Bitsichi) is a former tin mining location with relatively high background radiation (Babalola, 1984; Sanni et al., 1985; Oresegun and Babalola, 1990, 1993; Farai and Jibiri, 2000; Farai and Ademola, 2001; Jibiri, 2001), although no data presently exist on the radionuclide contents of food crops in this area. Soils in the area are rich in natural radionuclides and it is possible that they may accumulate in food crops above desirable levels. The aim of the present study is, therefore, to determine the activity concentrations of ^{40}K, ^{238}U and ^{232}Th in different agricultural crops grown in the area and to estimate the effective ingestion dose to individuals consuming locally produced food in the area.

2. Materials and methods

2.1. Sampling

A map of Jos-Plateau showing the location of the sampling site at Bitsichi is shown in Fig. 1. The local food crops grown in the area were identified and, to ensure good coverage, the entire area was divided into six sub-areas of about 3 km^2. The full range of food items identified could not be collected at each sampling site since no single sub-area contained all the food types grown in the area as a whole. However, an effort was made to ensure adequate collection of representative samples of the food crops identified in the

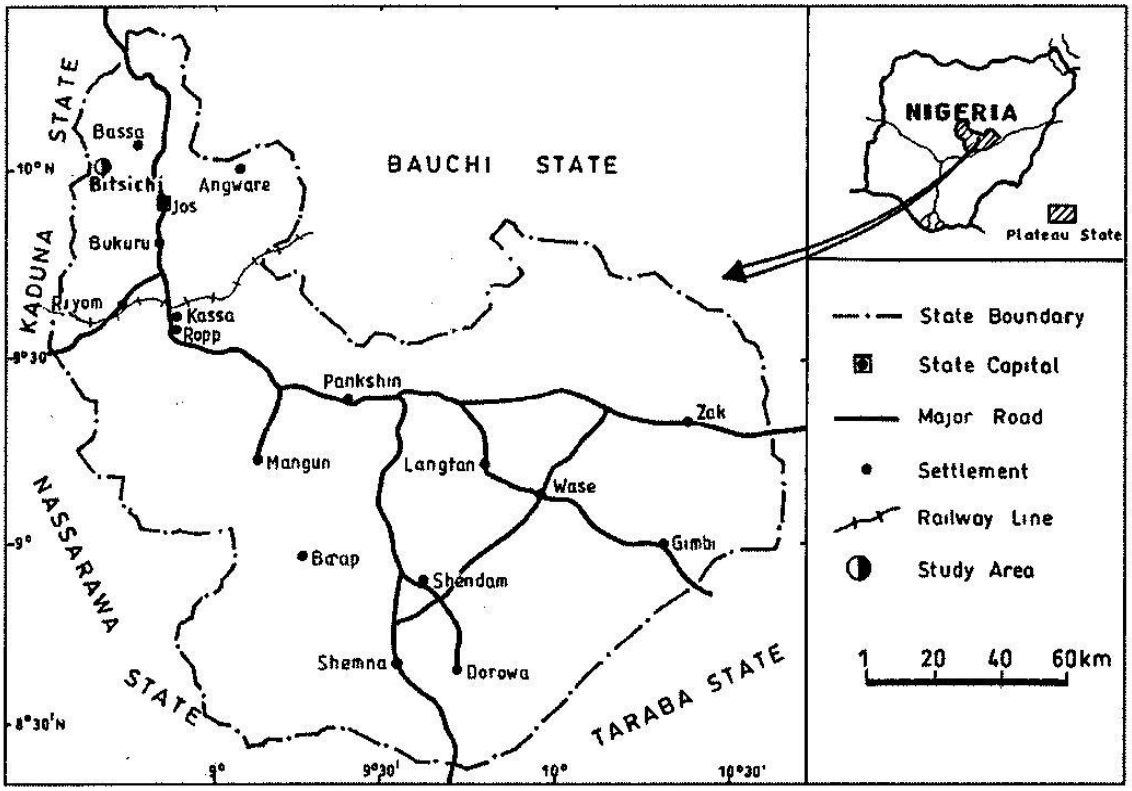

Fig. 1. Map of Jos-Plateau, Nigeria showing the study location (Bitsichi).

study area. The different food items collected and the number of each sample is presented in Table 1. Soil samples were collected to a depth of 150 mm from four different points in the farms where food samples were collected and, thereafter, thoroughly mixed together to provide a representative sample for that site. Aerial dose rate measurements were also performed in the farms using a precalibrated survey meter (Morgan Series 1000 – mini rad meter by Mini Instruments Ltd., England).

The soil samples, after drying for several days at room temperature until a constant weight was reached, were crushed to pass through a 2 mm mesh sieve. The sieved samples were transferred into uncontaminated empty cylindrical plastic containers of uniform size (60 mm height by 65 mm diameter) and sealed for a period of about 4 weeks. This was done to allow ^{222}Ra and its short-lived daughters to reach secular equilibrium prior to gamma spectroscopy. Since the study focused on human ingestion of foods grown and consumed by the population in the study area, only the edible parts of the food crops were prepared for analysis. For instance, the peel of cassava tuber, yam tuber and cocoyam were all discarded. The items were thereafter air dried to a constant weight, then homogenized and transferred into calibrated geometry sample containers and sealed in the same way as the soil samples.

The food samples, after preparation, represent the raw foodstuffs which are sold in local markets to consumers. Consumption of these foods without any further preparation would deliver the maximum ingestion dose to consumers. However, to investigate any possible removal of radionuclides during cooking, parts of the food items were prepared using typical local practices. For instance, cassava is made into fufu, yam into dafefen-doya (boiled yam), maize into soyeyen-masara (fried) or dafefen-masara (boiled) and groundnut into kulikuli (nut ball). After preparing samples in these ways they were analyzed for their radionuclide contents.

2.2. Radioactivity determination

The samples (food items, soil and local diets) were counted for 36,000 s (10 h) using a low-level gamma spectrometry system consisting of a 76 mm × 76 mm NaI (Tl) detector (Model No. 802-series,

Table 1
The different samples of food items collected and their food group

Food group	Sub-food type: group/food	Scientific names	Number of samples
Grains/cereals	Dyare		2
	Millet	*Pennisetum glaucum*	3
	Maize	*Zea mays*	4
	Guinea corn	*Sorghum bicolor* L.	2
	Acha	*Digitaria exilis stapf*	4
Vegetables	Tuberous		
	Sweet potato	*Ipomoea batatas*	3
	Irish potato	*Solanum tuberosum*	4
	General		
	Okra	*Abelmoschus esculentus*	3
	Tomato	*Lycopersicon esculentum*	3
	Pepper	*Capsicum annum*	3
	Garden egg	*Solanum gilo*	2
	Leafy		
	Kuca		3
Tubers	Yam	*Dioscorea* sp.	4
	Cassava	*Manihot esculenta*	4
	Cocoyam	*Colocasia esculenta*	3
Legumes	Groundnut	*Arachis hypogaea* Linn.	3
	Local bean (Sword beans)	*Canavalia ensiformis*	2
	Soya beans	*Glycine max* Merr.	3

Kuca and Dyare are local vegetable and cereal crops, respectively.

Canberra Inc.) coupled to a Canberra Series 10 plus Multichannel Analyzer (MCA) (Model No. 1104) through a preamplifier base. The detector has a resolution of about 8% at 0.662 MeV, which is capable of distinguishing the gamma ray energies of the radionuclides of interest in this study. The photopeak at 1.46 MeV was used for the measurement of ^{40}K while those at 1.76 MeV peak from ^{214}Bi and 2.614 MeV from ^{208}Tl were used for the measurement of ^{238}U and ^{232}Th, respectively. The net area under each photopeak, after background corrections, was used to calculate the activity concentration of each radionuclide in the food and soil samples. The activity concentration in the samples was obtained using the following expression (Olomo et al., 1994; Akinloye and Olomo, 2000):

$$C\,(\mathrm{Bq\,kg^{-1}}) = \frac{C_n}{\varepsilon P_\gamma M_s} \tag{1}$$

where C is the activity concentration of the radionuclide in the sample, C_n is the count rate under each photopeak due to each radionuclide, ε is the detector efficiency for the specific γ-ray, P_γ is the absolute transition probability of the specific γ-ray and M_s is the mass of the sample (kg). The mass of samples analyzed ranged between 80 g and 200 g for the food samples while a uniform mass of 200 g was used for the soil samples.

3. Results and discussion

3.1. Radioactivities and external dose rates

The activity concentrations of the radionuclides in the soil samples are shown in Table 2 while those in the food items and the diets are presented in Tables 3 and 4, respectively. The

Table 2
Activity concentrations (Bq kg^{-1}, dry weight) of ^{40}K, ^{238}U and ^{232}Th and total effective dose rates in the farm soil

Locations	^{40}K	^{238}U	^{232}Th	Effective dose rate (μSv h^{-1})
Farm 1	93.0 ± 9.6	145.2 ± 16.3	373.5 ± 8.9	0.2
Farm 2	135.7 ± 7.1	175.1 ± 19.6	515.2 ± 10.1	0.3
Farm 3	166.4 ± 12.4	10.9 ± 15.2	122.7 ± 11.2	0.07
Farm 4	128.8 ± 17.2	72.5 ± 13.8	168.4 ± 7.8	0.1
Farm 5	BDL	427.1 ± 12.4	1036.5 ± 8.8	0.6
Farm 6	55.1 ± 11.5	470.6 ± 10.9	2189.5 ± 9.2	1.2

BDL, below detection limit.

errors in Tables 2 and 3 are combined uncertainties in the counting measurements. As shown in Table 2, ^{232}Th exhibited the highest activity concentrations in soils at virtually all the sampling sites. This contrasts with previous studies in which ^{40}K contents have usually been found to be higher in areas with lower background radioactivities (Olomo et al., 1994; Jibiri and Bankole, 2006). Table 3 shows that ^{40}K was highest in all the food samples despite having the lowest activity concentrations in soil samples. This may be attributed, in part, to the heavy use of NPK fertilizers by farmers to improve crop yield following impoverishment of the soil by decades of mining operations in the area (Pasquini and Alexander, 2005; Yusuf et al., 2004). The activity concentrations of ^{40}K, ^{238}U and ^{232}Th in the food crops from this area were about 10× higher than those obtained in other parts of the country. For instance, in tuber products the radionuclide levels varied from 10.6 Bq kg^{-1} to 46.4 Bq kg^{-1} for ^{40}K, 0.5 Bq kg^{-1} to 2.7 Bq kg^{-1} for ^{238}U and from BDL to 1.4 Bq kg^{-1} for ^{232}Th (Akinloye and Olomo, 2000) while in cereal

Table 3
Activity concentrations of radionuclides in crops (Bq kg^{-1}, dry weight) and the estimated total effective dose from ingestion of the food items

Food items	^{40}K	^{238}U	^{232}Th	Effective dose (μSv y^{-1})
Maize	243.2 ± 21.2	34.1 ± 14.2	BDL	63.5
Millet	144.4 ± 12.8	4.6 ± 3.4	BDL	39.4
Acha (Hungry rice)	BDL	BDL	BDL	–
Dyare	179.4 ± 25.3	4.7 ± 1.1	8.1 ± 3.2	1.9
Guinea corn	85.9 ± 25.6	5.2 ± 1.3	7.6 ± 1.6	111.9
Yam	684.5 ± 40.6	85.5 ± 10.2	89.8 ± 6.2	2164.1
Cocoyam	537.1 ± 18.1	34.0 ± 15.1	33.3 ± 7.2	81.0
Cassava	539.6 ± 21.2	27.4 ± 9.4	22.2 ± 5.2	519.4
Sweet potato	423.7 ± 30.8	23.6 ± 11.1	35.6 ± 12.3	169.6
Irish potato	494.4 ± 22.1	10.7 ± 3.6	17.1 ± 9.8	22.2
Okra	213.0 ± 19.4	BDL	BDL	–
Tomato	158.9 ± 28.9	13.9 ± 6.4	9.6 ± 4.1	27.4
Pepper	132.4 ± 19.2	4.5 ± 3.8	BDL	9.4
Garden egg	122.3 ± 22.2	32.1 ± 19.2	BDL	–
Kuca	80.6 ± 17.2	10.4 ± 7.1	BDL	–
Soya beans	546.8 ± 28.6	8.3 ± 4.2	BDL	9.4
Groundnut	398.6 ± 12.9	7.4 ± 3.2	9.8 ± 3.4	12.8
Local beans	453.6 ± 15.8	9.4 ± 2.4	18.9 ± 6.4	0.2

–, MAC for the food items is not available; BDL, below detection limit.

Table 4
Activity concentrations of radionuclides (Bq kg^{-1}, dry weight) in prepared foods and percent reduction in radionuclide activity concentrations due to cooking

Food diets	^{40}K	^{238}U	^{232}Th
Alibor	169.9 (68.5)	24.7 (9.9)	5.1 (77.0)
Fufu	275.5 (48.9)	47.6 (−73.8)	17.2 (22.6)
Fried maize	60.3 (75.0)	12.7 (62.6)	BDL
Cooked maize	98.6 (59.5)	18.1 (47.1)	BDL
Boiled cocoyam	403.8 (24.8)	BDL	BDL
Boiled Irish potato	493.6 (0.002)	21.1 (−97.2)	6.5 (62.2)
Boiled sweet potato	244.2 (42.4)	BDL	6.5 (81.8)
Fried groundnut	488.5 (22.6)	34.2 (−362.2)	BDL
Kulikuli	207.5 (48.0)	BDL	BDL
Boiled groundnut	268.5 (32.6)	19.1 (−158.2)	BDL
Boiled yam	468.1 (31.6)	21.3 (75.1)	BDL

BDL, below detection limit.

crops the values of the radionuclides varied from 36.4 Bq kg^{-1} to 186.9 Bq kg^{-1} for ^{40}K, 0.2 Bq kg^{-1} to 1.4 Bq kg^{-1} for ^{238}U and from 0.3 Bq kg^{-1} to 1.8 Bq kg^{-1} for ^{232}Th (Arogunjo, 2003). In cooked foods, the activity concentrations of ^{40}K, ^{238}U and ^{232}Th ranged between 60.32 Bq kg^{-1} and 493.63 Bq kg^{-1}, between BDL and 47.6 Bq kg^{-1} and between BDL and 17.2 Bq kg^{-1}, respectively. As shown in Table 4, there appears to be removal of radionuclides from foodstuffs during cooking when compared with the values in Table 3. The percent reductions ranged between 0.002 and 75% for ^{40}K, 9 and 75% for ^{238}U and 22 and 82% for ^{232}Th. However, there were also apparent increases in ^{238}U activities in some foodstuffs, indicated by negative 'percentage reduction' values. This may be due to the presence of ^{238}U in water used for cooking although this was not investigated as part of the present study but may be examined in future work. The overall conclusion from this part of the study is that cooking can have a major influence on the radionuclide composition of foodstuffs.

The activity concentrations of ^{40}K, ^{238}U and ^{232}Th measured in each of the soil samples from the farms indicate the quantity of radioactivity present but do not provide a measure of radiation risk in the form of an absorbed dose rate. The absorbed dose rate, D (nGy h^{-1}) in air at 1 m above ground level due to the presence of ^{238}U, ^{232}Th and ^{40}K in the soil samples at each site was calculated using the following equation (UNSCEAR, 2000):

$$D = aC_U + bC_{Th} + cC_K + dC_{Cs} \quad (2)$$

where a is the dose rate per unit ^{238}U activity concentration (4.27×10^{-10} Gy h^{-1}/Bq kg^{-1}), C_U is the concentration of ^{232}U in the sample (Bq kg^{-1}), b is the dose rate per unit ^{238}Th activity concentration (6.62×10^{-10} Gy h^{-1}/Bq kg^{-1}), C_{Th} is the concentration of ^{232}Th in the sample (Bq kg^{-1}), c is the dose rate per unit ^{40}K activity concentration (0.43×10^{-10} Gy h^{-1}/Bq kg^{-1}), C_K is the concentration of ^{40}K in the sample (Bq kg^{-1}), d is the dose rate per unit ^{137}Cs activity concentration (0.30×10^{-10} Gy h^{-1}/Bq kg^{-1}) and C_{Cs} is the concentration of ^{137}Cs in the sample (Bq kg^{-1}). Since ^{137}Cs was not detected in any of the samples the last term in Eq. (2) was assumed to be zero. The absorbed dose rate (nGy h^{-1}) in air at 1 m above the ground determined at each farm does not directly give the radiological hazard to which an individual is exposed. There are two additional factors that must be considered. The first is a factor which converts Gy to Sv that accounts for the biological effectiveness of the dose in causing damage

in human tissue. The second is the occupancy factor that specifies the proportion of the total time spent outdoors. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recommended 0.7 Sv Gy^{-1} as the first factor and 0.2 as the second factor. According to Adejuwon (2002), an average of 10 h per day is spent by farmers from this area and generally for peasant farmers in the country. As such an outdoor occupancy factor of 0.4 ($\approx$10 h per day) has been assumed in this study. Using these assumptions, the total effective gamma dose due to radionuclides in the soil at the different farms investigated ranged between 0.07 μSv h^{-1} and 1.16 μSv h^{-1}, giving an annual external dose of 228 μSv and 4065 μSv, respectively. The aerial dose rates obtained using a survey meter were found to vary between 0.50 μSv h^{-1} and 1.47 μSv h^{-1}. The dose rate estimates from both in situ and soil measurements are in reasonable agreement and indicate dose rates 20× higher than the world average terrestrial value of 0.055 μSv h^{-1} (UNSCEAR, 2000). The major contributor to gamma radiation exposure in the area is ^{232}Th.

3.2. Effective dose due to ingestion

Effective dose is a useful concept that enables the radiation doses from different radionuclides and from different types and sources of radioactivity to be added. It is based on the risks of radiation induced health effects and the use of the International Commission on Radiological Protection (ICRP) metabolic model that provides relevant conversion factors to calculate effective doses from the total activity concentrations of radionuclides measured in foods (ICRP, 1994, 1996). Estimates of the radiation induced health effects associated with intake of radionuclides in the body are proportional to the total dose delivered by the radionuclides while resident in the various organs. Radiation doses ingested are obtained by measuring radionuclide activities in foodstuffs (Bq kg^{-1}) and multiplying these by the masses of food consumed over a period of time (kg d^{-1} or kg y^{-1}). A dose conversion factor (Sv Bq^{-1}) can then be applied to give an estimate of ingestion dose. Thus, according to Till and Moore (1988), the ingested dose is given by:

$$H_{T,r} = \left(U^{Bl}C_r^{Bl} + U^{Pf}C_r^{Pf} + U^{Mi}C_r^{Mi} + \cdots\right)g_{T,r} \tag{3}$$

Eq. (3) can rewritten as:

$$H_{T,r} = \sum\left(U^i C_r^i\right)g_{T,r} \tag{4}$$

where i denotes a food group, the coefficients U^i and C_r^i denote the consumption rate per year (kg) and activity concentration of the radionuclide (Bq), respectively, and $g_{T,r}$ is the dose coefficient for intake by ingestion of radionuclide r (Sv Bq^{-1}). The values of g for ^{40}K, ^{238}U, ^{232}Th and ^{137}Cs are 5.9×10^{-9} Sv Bq^{-1}, 4.8×10^{-8} Sv Bq^{-1}, 2.3×10^{-7} Sv Bq^{-1} and 1.3×10^{-8} Sv Bq^{-1}, respectively, for adult members of the public (ICRP, 1994, 1996; RIFE, 2005). Using these conversion factors, the effective doses due to ingestion were estimated and these values are presented in Table 3. The food consumption statistics used for the different food crops in Nigeria, based on Federal Office of Statistics (FOS) and Food and Agriculture Organization (FAO) data, are presented in Table 5. In this study, the calculation of individual doses and risks from ingestion pathways carried out were based on the assumption that all food is consumed at the point of production and that the required amount of food is produced in the given location. In essence, foodstuffs are obtained wholly from local sources.

Table 5
The mean annual consumption (MAC) values per kg per person

Food type	MAC[a]
Maize	20.67
Millet	36.24
Rice	26.35
Guinea corn	44.70
Other cereals	0.60
Cassava	115.46
Irish potatoes	3.24
Sweet potatoes	14.35
Yam	75.15
Other roots	6.50
Wheat	18.55
Beans	0.02
Soya beans	2.58
Groundnut	2.76
Tomatoes	7.19
Pepper	8.06

[a] Data were collected from the Federal Office of Statistics Nigeria (2006).

Furthermore, in estimating doses to individuals from agricultural food products, it is usually important to consider the peculiarity of the food availability to such an individual and the nature of the environment from which he/she derives his/her food products. The three types of individual usually considered are:

(i) Control individuals whose diet consists of food grown on undisturbed soil.
(ii) Local individuals who obtain 10% of their food from a disturbed soil.
(iii) Theoretical 'maximally exposed' individuals whose diet is obtained solely from food grown on disturbed soil.

This study focuses on a mining area with disturbed soils and the assessment of dose is based on assumptions (ii) and (iii). From a radiation protection perspective, a conservative estimate of dose (assumption (iii)) is important in developing a Protective Action Guide (PAG) and in planning and legislation of food policy and administration (Fernandez et al., 2004). A PAG is defined as an action or measure taken to avoid exposure to radiation that would occur from future ingestion of foods contaminated with radioactive materials due to local or international releases.

The estimated total effective dose due to the intake of radionuclides varied from 0.2 $\mu Sv\ y^{-1}$ in local beans to 2164.1 $\mu Sv\ y^{-1}$ in yam. The tuber crops were found to deliver a higher ingestion dose than the other crop types. It is, however, expected that lower doses will be delivered after cooking and preparation of foodstuffs, as evident from the percent reductions in radionuclide activity concentrations shown in Table 4. Generally, the dose from ingestion of radionuclides can be considered to be low when compared with natural external exposures of about 2000 $\mu Sv\ y^{-1}$.

4. Conclusion

The effective dose due to ingestion of crops grown in an area of high background radiation (Bitsichi town, an old tin mining area on the Jos-Plateau, Nigeria) has been estimated based on

measured activity concentrations of ^{40}K, ^{238}U and ^{232}Th in different food crops. The activity concentration of ^{40}K was highest in all the food crops and this could be due in part to the use of fertilizer by farmers to improve crop yields on the farms in the area. Tuber crops were found to deliver a higher ingestion dose than cereal crops which constitute the major food type of nutritional importance in the area under study. The external dose on the farms due to soil radioactivity and estimated ingestion dose related to local food products were relatively high when compared to studies in other parts of the country. However, they are considered to be sufficiently low to result in negligible harmful effects when dietary habits, food choices and occupancy times on local farms are taken into account.

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APPENDIX 2

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Radiological hazard indices due to activity concentrations of natural radionuclides in farm soils from two high background radiation areas in Nigeria

N.N. Jibiri*

Radiation and Health Physics Research Laboratory
Department of Physics
University of Ibadan
Ibadan, Nigeria
E-mail: jibirinn@yahoo.com
E-mail: nnamdi.jibiri@mail.ui.edu.ng
*Corresponding author

S.K. Alausa

Department of Physics
Olabisi Onabanjo University
Ago-Iwoye, Nigeria
E-mail: alausakunle@yahoo.com

I.P. Farai

Radiation and Health Physics Research Laboratory
Department of Physics
University of Ibadan
Ibadan, Nigeria
E-mail: ipfarai@yahoo.co.uk
E-mail: ip.farai@mail.ui.edu.ng

Abstract: Abeokuta and Jos Plateau, towns in the southwestern and northern parts of Nigeria, respectively, are situated in areas of high background radiation. The use of farm soil for the construction of dwellings by local residents and for agricultural purposes in these areas may present scenarios for both enhanced external and internal exposure pathways to the population. In order to assess the gamma radiation exposure levels, soil samples from 65 farms in Jos Plateau and 47 farms in Abeokuta were collected. Using gamma-ray spectroscopy the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the samples were determined. From the activity concentrations of these radionuclides, the absorbed gamma dose rates were calculated. The obtained mean total absorbed gamma dose rates varied between 194 ± 59 nGy h^{-1} and 350 ± 270 nGy h^{-1} in Jos Plateau, whereas in Abeokuta, it was 167 ± 140 nGy h^{-1}. These results, along with the results of the estimated annual effective dose rates, radium equivalent (Ra_{eq}), external hazard index (H_{ex}), internal hazard index (H_{in}) and gamma index (I_γ), are presented in this paper. The results of this study indicate that the populations in the investigated areas are likely subjects for high radon burden in their dwellings.

Keywords: tin tailings; natural radionuclides; activity concentration; building construction; radiation; gamma dose rates; farm soil; radiological hazard indices; Nigeria.

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Biographical notes: Nnamdi Norbert Jibiri holds a BSc in Physics from the University of Jos Plateau, Nigeria, and an MSc and PhD in Radiation and Health Physics from the University of Ibadan, Nigeria. He is a Lecturer in the Physics Department of the University of Ibadan. He has over 15 years of university teaching and research experience and is involved in postgraduate training in the Department of Physics and Professional Masters training in Radiation Protection. Presently, he is the Assistant Head of the Radiation and Health Physics Research Unit of his department.

Shamsudeen Kunle Aluasa holds a BSc in Physics from Olabisi Onabanjo Univeristy, Ago-Iwoye, Nigeria, and an MSc in Radiation and Health Physics from the University of Ibadan, Nigeria. He is a Lecturer in the Department of Physics of Olabisi Onabanjo University and has about five years of university teaching experience. He is a PhD student in the Department of Physics, the University of Ibadan, with bias in Radiation and Health Physics.

Idowu Peter Farai holds a BSc in Physics from the University of Nigeria, Nsukka, Nigeria, and an MSc and PhD in Radiation and Health Physics from the University of Ibadan, Nigeria. He is an Associate Professor at the Department of Physics, the University of Ibadan. He has over 25 years of university teaching and research experience. He produced over seven PhD graduates, is involved in postgraduate training at the Department of Physics and is also involved in Professional Masters training in Radiation Protection. He is presently the Head of Department of Physics, the University of Ibadan.

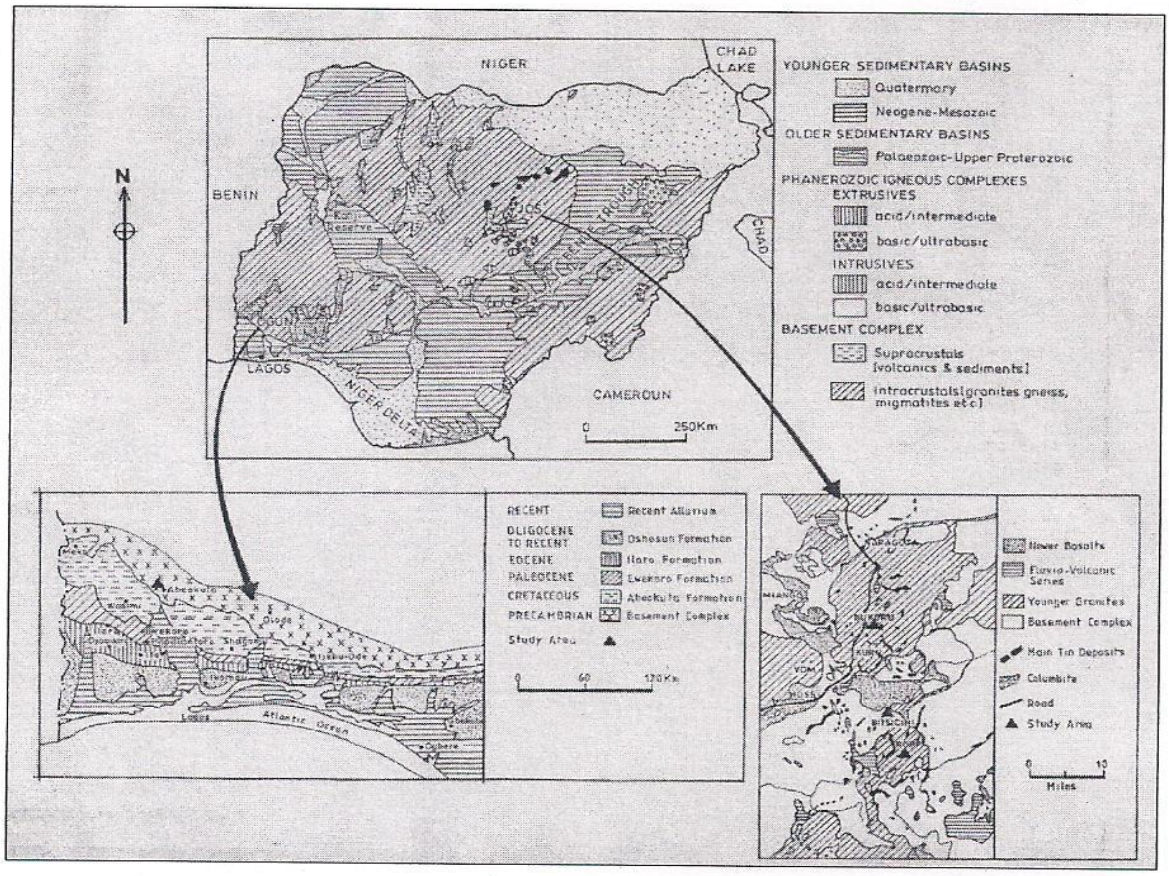
1 Introduction

The great global interest in the study and survey of naturally occurring radiation and environmental radioactivity had been essentially based on the importance of using the results from such studies for the assessment of public radiation exposure rates and the performance of epidemiological studies, as well as reference radiometric data relevant in studying the possible changes in environmental radioactivity due to nuclear, industrial and other human technology-related activities (UNSCEAR, 2000). It has been established that out of the total radiation dose that the world population receives, about 96.1% is from natural sources and the remainder is from human-made sources (Chougankar *et al.*, 2003). The natural environmental radioactivity in a location and its associated external exposure due to gamma radiation depend primarily on its geological and geographical conditions. It is related to the composition of each lithologically separated area and the content of the rock from which the soil originates (Whicker, 1983; Wollenberg and Smith, 1990). Therefore, specific concentration levels of terrestrial radiation differ in the soil of each region of the world (Akhtar *et al.*, 2004; Tufail *et al.*, 2007; Shiva Prasad *et al.*, 2008).

In Nigeria, half of the land area of 923 768 km^2 is underlain by crystalline rocks or basement complex and the remaining half by sedimentary rocks. The basement complex is of Precambrian age and composed primarily of metamorphic and igneous rocks such as granites, gneisses and migmatites (Rahaman, 1988). There are also extensive occurrences of schist, phyllites, quartzite and marble. Two groups of granites can be distinguished in the geological setting of Nigeria. They are the older granites and the younger granites that are non-organic (Badejoko, 1975; Elueze, 1992).

Abeokuta is a town in the southwestern part of Nigeria (Lat. 5° 28′N to 8° 30′N and Long. 3° 22′E to 5° 46′E), whereas Jos Plateau is in the northern part (Lat. 7° 45′N to 12° 00′N and Long. 7° 32′E to 11° 10′E). Both are situated on a basement complex with a characteristically granite base (Rahaman, 1988). It is well known that granites contain high concentrations of uranium, thorium and potassium (Lopez *et al.*, 2004; Yang *et al.*, 2005). The uranium and thorium are incorporated into the rocks in the crystallisation of the last magmas and residual solutions since their large ionic radii hinders them from crystallising in the early silicates (Shiva Prasad *et al.*, 2008). Figure 1 shows the geological formations of Jos Plateau and Abeokuta. The distribution of these rocks and the resulting soil and their modifications represent different radioactive environments across the two areas under investigation, since environmental radioactivity is determined largely by top soil radioactivity and other geochemical processes (Wollenberg and Smith, 1990).

Figure 1 The generalised geological map of Nigeria showing the distributions in Abeokuta and Jos Plateau with its associated tin fields (see online version for colours)



The presence of radionuclides in soil is a source of the radioactivity intake of human beings by direct and indirect pathways. Direct exposure pathways arise from the external soil in the environment or when used in soil-based bricks in the construction of dwellings. Indirect exposure occurs through plant uptake and subsequent consumption by humans, inhalation by airborne dust load during farming and also through the inadvertent ingestion of soil particles during farming processes (Ahmed and El-Arabi, 2005; Righi and Bruzzi, 2006; Mlwilo *et al.*, 2007). Abeokuta and Jos Plateau have been identified to be situated in areas with high background radiation (Farai and Jibiri, 2000). The realisation of high radiation levels in these towns necessitated various studies on the measurements of radioactivity in different environmental matrices in both cities and their environs (Farai and Ademola, 2001; Obed *et al.*, 2005; Farai and Vincent, 2006; Jibiri *et al.*, 2007a–b; Jibiri and Agomuo, 2007). No attempt, however, has been made to particularly investigate the radioactivity in farm soil in the rural areas of these two cities. In this work, we have therefore carried out this initiative to assess the level of gamma radiation exposure from farm soil in the rural areas, considering the imperative that farm soil is used extensively in the construction of dwellings in a typical rural setting. Also, farm soil is considered an important pathway for both external and internal exposures to the rural populations during farming practices, as their sources of livelihood are dependent on the produce from the farms. The present study is, therefore, aimed at achieving the following objectives:

- determine the activity concentrations of natural radioactive elements in farm soil in the rural localities of the two high background radioactivity areas in Nigeria
- estimate the external gamma dose rates in the farm soils
- estimate the radiological hazard index parameters, radium equivalent, gamma index, external hazard index and internal hazard index
- provide an overall assessment of the suitability of the use of the farm soil in the construction of dwellings in the local communities.

2 Materials and methods

2.1 Soil sample collection

A presurvey was first carried out to delineate the farmlands where samples would be collected. The identified farmlands were such that they were evenly distributed and largely cover the areas under investigation. The separation distances between the chosen farmlands were between 250 m and 300 m. The criteria considered in choosing a particular farm for sampling were that the farmlands are in use for farming and are also closer to the local dwellings to endear the dwellers to use soil from the farms for construction purposes. At each farmland, soil samples were collected to a depth of 150 mm from three to five spots, with an average area of 2 m^2, each spot being separated from each other by at least 10 m. About 500 g of soil from each spot was collected. All the samples from each spot were mixed thoroughly as a composite sample representative of the farm. They were transferred into a polythene bag and taken to the laboratory for processing.

2.2 *Soil sample preparation*

At the laboratory, extraneous materials like plant materials, roots and pebbles were deliberately not removed. This was done so that all the contributing elements in the farm soil samples of the areas under investigation were retained in the analysis. The soil samples, along with the extraneous materials, were dried at 110°C in a temperature-controlled oven until there was no detectable change in the mass of the sample. The dried samples were thoroughly crushed, ground and pulverised into powder. The powder was passed through a 2 mm sieve. Due to the limited space of the detector shield, only 200 g of the soil samples (dry weight) were used for analysis. The samples were transferred after weighing to radon-impermeable cylindrical plastic containers of uniform size (60 mm height by 65 mm diameter) and were sealed for about 30 days. This was done in order to allow for radon and its short-lived progenies to reach secular radioactive equilibrium prior to gamma spectroscopy. The reference soil was also transferred to a container with the same material and dimensions as those used for the soil samples. This is to ensure that the geometric configuration remained the same. The standard reference soil sample used was prepared from Rocketdyne Laboratories California, USA, which is traceable to a mixed standard gamma source (Ref. No. 48722-356) by Analytic Inc. Atlanta, Georgia, USA.

2.3 *Activity determinations*

The soil samples were analysed using a 76 × 76 mm NaI(TI) detector crystal (Model No. 802 series, Canberra Inc.) enclosed in a graded 10 cm-thick Canberra lead shield. The detector was coupled to a Canberra Series 10 plus Multichannel Analyser (MCA) (Model No. 1104) through a preamplifier using 5 m connection co-axial cables. The detector has a resolution (Full Width at Half Maximum Height (FWHM)) of about 8% at an energy of 0.662 MeV (^{137}Cs), which is considered adequate to distinguish the gamma ray energies of interest in the present study. The choice of radionuclides to be detected was predicated on the fact that the NaI(Tl) detector used in this study had a modest energy resolution; hence, the photons emitted by them would only be sufficiently discriminated if their emission probability and energy were high enough and the surrounding background continuum was low enough. Therefore, the activity concentration of ^{214}Bi (determined from its 1.760 MeV γ-ray peak) was chosen to provide an estimate of ^{226}Ra (^{238}U) in the samples, while that of the daughter radionuclide ^{208}Tl (determined from its 2.615 MeV γ-ray peak) was chosen as an indicator of ^{232}Th. ^{40}K was determined by measuring the 1.460 MeV γ-rays emitted during its decay.

The samples were measured for a period of 10 h, after which the net area under the corresponding γ-ray peaks in the energy spectrum was used to compute the activity concentrations in the samples through the equation (Obed *et al.*, 2005; Jibiri *et al.*, 2007b):

$$C(Bq\,kg^{-1}) = kC_n, \tag{1}$$

where:

$$k = \frac{1}{\varepsilon P_\gamma M_s}$$

C = the activity concentration of the radionuclide in the sample given in Bq kg^{-1}
C_n = the count rate under the corresponding peak
ε = the detector efficiency at the specific γ-ray energy
P_γ = the absolute transition probability of the specific γ-ray
M_s = the mass of the sample (kg).

The detection limit of a measuring system describes its operating capability without the influence of the sample. With the measurement system used in the present work, the obtained detection limits were 17.3 Bq kg^{-1}, 4.2 Bq kg^{-1} and 5.1 Bq kg^{-1} for ^{40}K, ^{226}Ra and ^{232}Th, respectively. Values below these numbers were taken in this work as being Below the Detection Limit (BDL) of the detector.

3 Results and discussions

3.1 Specific radioactivity

The measured activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the farm soil samples from different farmlands in Bitsichi, Bukuru and Ropp are presented, along with the statistical measurement uncertainties in Tables 1, 2 and 3, respectively, while the measured concentrations of the radionuclides for Abeokuta are presented in Table 4. The error terms in the mean values in the tables are the standard deviations of the range of values across the farms. As could be seen from the tables, the mean activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the Jos Plateau area comprising the three mining sites varied from 109 ± 28 Bq kg^{-1} (Bukuru) to 163 ± 92 Bq kg^{-1} (Bitsichi), 154 ± 56 Bq kg^{-1} (Bukuru) to 451 ± 368 Bq kg^{-1} (Bitsichi) and 466 ± 221 Bq kg^{-1} (Bitsichi) to 1062 ± 199 Bq kg^{-1} (Ropp), respectively. In Abeokuta, the obtained mean activity concentrations were 65 ± 29 Bq kg^{-1}, 184 ± 205 Bq kg^{-1} and 411 ± 341 Bq kg^{-1} for ^{226}Ra, ^{228}Th and ^{40}K, respectively.

The activity concentrations of the radionuclides (except ^{40}K) were highest in Bitsichi when compared with Ropp and Bukuru and also with Abeokuta. Generally, the values obtained for Ropp and Bukuru can be seen to be very similar and should ideally be approximately characteristic of Jos Plateau since they belong to the same geological formation. The relatively higher values recorded in Bitsichi when compared with those in Ropp and Bukuru may be attributed to the perceived variations in the environment resulting from past mining activities. On record, Bitsichi was mostly affected by the decades of mining operations in Jos Plateau; hence, some traces of tin tailings is observed in some of the farm soil samples from the area. This was reflected on the activity values of ^{232}Th and ^{238}U obtained for farms 12, 36 and 37 (Table 1). The tin tailings from the area have been found to contain very high concentrations of ^{232}Th and ^{238}U averagely between 16.8×10^2 and 72.2×10^3 Bq kg^{-1}, respectively (Oresegun and Babalola, 1990; 1993; Ademola, 2008b). Apparently, it could be seen that Jos Plateau and Abeokuta may be said to belong to the same geological formations, as characterised by the activity distribution levels of the natural radionuclides in this study.

Table 1 The activity concentrations due to ^{226}Ra, ^{232}Th and ^{40}K and gamma dose rates in the farm soil from Bitsichi

Farms	*^{226}Ra (Bq kg^{-1})*	*^{232}Th (Bq kg^{-1})*	*^{40}K (Bq kg^{-1})*	*Absorbed dose rate (nGy h^{-1})*	*Effective dose rate (mSv y^{-1})*
1	315 ± 24	180 ± 9	534 ± 34	277	0.33
2	217 ± 26	295 ± 15	778 ± 44	322	0.40
3	116 ± 21	128 ± 9	437 ± 29	154	0.19
4	149 ± 26	513 ± 17	326 ± 30	418	0.51
5	160 ± 28	527 ± 18	648 ± 43	446	0.55
6	89 ± 18	235 ± 11	810 ± 38	229	0.28
7	110 ± 26	581 ± 18	240 ± 25	442	0.54
8	198 ± 39	604 ± 18	329 ± 33	498	0.61
9	94 ± 21	236 ± 10	709 ± 37	227	0.28
10	125 ± 21	237 ± 11	808 ± 38	245	0.30
11	88 ± 24	389 ± 15	390 ± 31	321	0.39
12	143 ± 28	570 ± 18	477 ± 38	459	0.56
13	148 ± 26	219 ± 12	449 ± 34	227	0.28
14	91 ± 26	421 ± 16	352 ± 32	333	0.41
15	146 ± 29	706 ± 20	542 ± 41	553	0.68
16	67 ± 22	247 ± 12	250 ± 23	204	0.25
17	180 ± 26	394 ± 15	623 ± 40	364	0.45
18	82 ± 20	144 ± 9	313 ± 24	144	0.18
19	152 ± 21	101 ± 8	389 ± 28	148	0.18
20	129 ± 20	163 ± 9	750 ± 36	195	0.24
21	163 ± 23	210 ± 11	352 ± 28	224	0.27
22	127 ± 20	93 ± 7	631 ± 34	143	0.18
23	132 ± 23	328 ± 13	761 ± 39	306	0.38
24	304 ± 29	574 ± 19	370 ± 34	525	0.64
25	256 ± 27	463 ± 17	663 ± 42	445	0.55
26	201 ± 24	252 ± 11	652 ± 37	281	0.34
27	223 ± 27	494 ± 17	906 ± 47	461	0.57
28	157 ± 23	272 ± 13	741 ± 39	279	0.34
29	140 ± 21	156 ± 8	452 ± 29	182	0.22
30	145 ± 23	275 ± 13	483 ± 35	101	0.12
31	86 ± 24	377 ± 15	482 ± 31	307	0.38
32	145 ± 16	374 ± 9	93 ± 10	313	0.38
33	175 ± 19	515 ± 10	136 ± 7	422	0.51
34	109 ± 15	123 ± 8	166 ± 12	93	0.11
35	73 ± 14	168 ± 8	129 ± 17	148	0.18
36	427 ± 12	1036 ± 9	BDL	868	1.07
37	471 ± 11	2190 ± 9	55 ± 12	1653	2.02
Mean	163 ± 92	451 ± 368	466 ± 221	350 ± 270	0.43 ± .033

Table 2 The activity concentrations due to ^{226}Ra, ^{232}Th and ^{40}K and gamma dose rates in the farm soil from Bukuru

Farms	*^{226}Ra (Bq kg^{-1})*	*^{232}Th (Bq kg^{-1})*	*^{40}K (Bq kg^{-1})*	*Absorbed dose rate (nGy h^{-1})*	*Effective dose rate (mSv y^{-1})*
1	137 ± 23	204 ± 12	1077 ± 42	240	0.29
2	114 ± 23	247 ± 12	734 ± 36	244	0.29
3	106 ± 20	69 ± 6	753 ± 33	124	0.15
4	97 ± 20	79 ± 6	614 ± 30	120	0.15
5	146 ± 23	245 ± 11	1334 ± 43	282	0.35
6	51 ± 20	BDL	824 ± 37	57	0.07
7	157 ± 22	225 ± 10	597 ± 31	241	0.30
8	99 ± 18	238 ± 11	1500 ± 47	264	0.32
9	136 ± 21	152 ± 9	953 ± 36	200	0.25
10	119 ± 19	189 ± 10	1238 ± 45	229	0.28
11	80 ± 17	124 ± 8	990 ± 41	159	0.18
12	84 ± 18	137 ± 9	1138 ± 43	175	0.21
13	81 ± 18	160 ± 9	823 ± 38	176	0.22
14	122 ± 16	166 ± 10	1154 ± 43	212	0.26
Mean	109 ± 28	154 ± 56	981 ± 263	194 ± 59	0.24 ± 0.08

Table 3 The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K and gamma dose rates in the farm soil from Ropp

Farms	*^{226}Ra (Bq kg^{-1})*	*^{232}Th (Bq kg^{-1})*	*^{40}K (Bq kg^{-1})*	*Absorbed dose rate (nGy h^{-1})*	*Effective dose rate (mSv y^{-1})*
1	87 ± 18	85 ± 6	831 ± 35	129	0.16
2	105 ± 22	124 ± 8	942 ± 41	167	0.20
3	43 ± 19	66 ± 6	1110 ± 41	112	0.14
4	60 ± 15	155 ± 14	527 ± 21	151	0.19
5	44 ± 14	118 ± 7	530 ± 21	120	0.15
6	76 ± 16	145 ± 8	324 ± 17	142	0.17
7	168 ± 27	150 ± 9	1854 ± 53	251	0.31
8	110 ± 25	160 ± 10	1572 ± 48	220	0.27
9	136 ± 27	107 ± 8	1796 ± 53	206	0.25
10	115 ± 30	116 ± 8	881 ± 33	162	0.20
11	196 ± 27	115 ± 8	1515 ± 49	225	0.28
12	136 ± 27	151 ± 10	1393 ± 47	218	0.27
13	163 ± 34	401 ± 16	618 ± 44	362	0.44
14	293 ± 34	194 ± 11	525 ± 32	276	0.34
Mean	129 ± 65	147 ± 75	1062 ± 199	196 ± 70	0.24 ± 0.08

Table 4 The activity concentrations due to ^{226}Ra, ^{232}Th and ^{40}K and gamma dose rates in the farm soil from Abeokuta

Farms	*^{226}Ra (Bq kg^{-1})*	*^{232}Th (Bq kg^{-1})*	*^{40}K (Bq kg^{-1})*	*Absorbed dose rate (nGy h^{-1})*	*Effective dose rate (mSv y^{-1})*
1	50 ± 20	96 ± 7	266 ± 18	97	0.12
2	113 ± 33	141 ± 9	1302 ± 41	198	0.24
3	42 ± 9	97 ± 7	196 ± 15	91	0.11
4	94 ± 21	88 ± 6	302 ± 21	113	0.14
5	59 ± 19	26 ± 2	139 ± 12	48	0.06
6	54 ± 13	132 ± 9	581 ± 29	135	0.17
7	72 ± 23	164 ± 10	629 ± 31	166	0.20
8	43 ± 12	60 ± 5	1329 ± 42	115	0.14
9	54 ± 22	115 ± 8	296 ± 21	112	0.13
10	54 ± 22	160 ± 10	496 ± 27	150	0.18
11	87 ± 20	18 ± 2	330 ± 21	64	0.08
12	45 ± 8	BDL	681 ± 34	48	0.06
13	21 ± 9	69 ± 5	27 ± 3	56	0.07
14	112 ± 11	158 ± 9	1108 ± 40	200	0.25
15	67 ± 22	64 ± 5	402 ± 23	89	0.11
16	114 ± 20	119 ± 7	1099 ± 39	175	0.21
17	39 ± 10	52 ± 5	198 ± 16	60	0.07
18	60 ± 12	169 ± 11	750 ± 35	170	0.21
19	81 ± 20	101 ± 7	395 ± 23	119	0.15
20	43 ± 12	63 ± 5	147 ± 14	67	0.08
21	78 ± 18	25 ± 3	197 ± 17	59	0.07
22	69 ± 16	576 ± 19	338 ± 30	423	0.52
23	72 ± 21	23 ± 2	157 ± 13	53	0.07
24	50 ± 19	689 ± 24	384 ± 24	494	0.61
25	66 ± 15	86 ± 10	173 ± 16	92	0.11
26	51 ± 14	455 ± 18	365 ± 31	339	0.42
27	33 ± 12	20 ± 5	220 ± 19	37	0.05
28	90 ± 20	644 ± 23	288 ± 21	478	0.59
29	13 ± 3	387 ± 17	864 ± 44	298	0.37
30	51 ± 14	70 ± 6	203 ± 17	77	0.09
31	39 ± 16	83 ± 7	288 ± 22	84	0.10
32	88 ± 18	541 ± 19	231 ± 25	406	0.50
33	99 ± 16	99 ± 7	235 ± 20	118	0.14
34	32 ± 15	65 ± 6	259 ± 21	68	0.08
35	122 ± 26	102 ± 7	205 ± 18	129	0.16
36	81 ± 21	100 ± 7	418 ± 24	119	0.15
37	24 ± 9	15 ± 2	65 ± 7	23	0.02

Table 4 The activity concentrations due to ^{226}Ra, ^{232}Th and ^{40}K and gamma dose rates in the farm soil from Abeokuta (continued)

Farms	*^{226}Ra (Bq kg^{-1})*	*^{232}Th (Bq kg^{-1})*	*^{40}K (Bq kg^{-1})*	*Absorbed dose rate (nGy h^{-1})*	*Effective dose rate (mSv y^{-1})*
38	78 ± 10	45 ± 15	82 ± 8	67	0.08
39	21 ± 7	320 ± 3	481 ± 30	242	0.30
40	82 ± 12	41 ± 4	84 ± 8	66	0.08
41	73 ± 13	808 ± 24	954 ± 45	580	0.71
42	79 ± 19	63 ± 6	122 ± 10	81	0.10
43	120 ± 22	512 ± 21	458 ± 32	411	0.50
44	60 ± 11	41 ± 4	42 ± 4	55	0.06
45	85 ± 19	550 ± 19	1170 ± 46	451	0.55
46	66 ± 11	99 ± 7	120 ± 11	99	0.12
47	26 ± 14	332 ± 16	259 ± 21	242	0.30
Mean	65 ± 29	184 ± 205	411 ± 341	167 ± 140	0.40 ± 0.26

3.2 *Radiological assessments*

3.2.1 *External absorbed dose rates*

The external absorbed dose rate, D (nGy h^{-1}) in air at 1 m above the ground level for soil containing the concentrations of the radionuclides measured in the samples is calculated using the following equation (UNSCEAR, 2000; Mustapha *et al.*, 2007):

$$D_{ext} = \sum_R A_R DC_{ext,R}, \tag{2}$$

where $DC_{ext,R}$ is the coefficient of dose rate per unit activity concentration of radionuclide R (nGy h^{-1}/Bq kg^{-1}) and A_R is the concentration of the radionuclide R in the sample (Bq kg^{-1}). UNSCEAR (2000) prescribed the $DC_{ext,R}$ coefficient of ^{226}Ra as 4.27×10^{-10} Gy h^{-1}/Bq kg^{-1}, ^{232}Th as 6.62×10^{-10} Gy h^{-1}/Bq kg^{-1}), ^{40}K as 0.43×10^{-10} Gy h^{-1}/Bq kg^{-1} and ^{137}Cs as 0.30×10^{-10} Gy h^{-1}/Bq kg^{-1}). Since ^{137}Cs was not detected in any of the samples, its coefficient was taken as zero. Using Equation (2) and the activity concentrations of the radionuclides in Tables 1 to 4 for each area, the total absorbed dose rates were calculated for each farm. The results are presented in Tables 1 and 2 for Bitsichi and Bukuru, respectively, whereas those for Ropp and Abeokuta are presented in Tables 3 and 4, respectively. The average total absorbed dose rates (as could be seen from the tables) is 350 ± 270 nGy h^{-1} for Bitsichi, 194 ± 59 nGy h^{-1} for Bukuru, 196 ± 70 nGy h^{-1} for Ropp and 167 ± 140 nGy h^{-1} for Abeokuta. These values are two to five orders of magnitude greater than the world average value of 59 nGy h^{-1} (UNSCEAR, 2000).

3.2.2 *Outdoor effective dose*

The absorbed γ-dose rates in air are usually related to the human-absorbed γ-dose in order to assess radiological implications. In assessing the outdoor effective dose equivalent to the members of the population, two important factors were considered. The first is a

factor that converts the absorbed dose rates (Gy h^{-1}) in air to human outdoor effective dose rates (Sv y^{-1}), while the second factor gives the proportions of the total time for which the typical individual is exposed to outdoor or indoor radiation. The United Nations Scientific Committee on the Effect of Atomic Radiation (UNSCEAR, 2000) has recommended 0.7 Sv Gy^{-1} as the value of the first factor and 0.2 and 0.8 for the outdoor and indoor occupancy factors, respectively. This second factor implies that the average individual spends only 4.8 h (about 5 h per day) outdoors. In this work, only the outdoor exposure from γ-ray sources due to the concentrations of primordial radionuclides in the soil were considered. The effective dose rate resulting from the absorbed dose rate values was calculated using the following relation:

$$E_{ext} = T f Q D_{ext} \varepsilon, \tag{3}$$

where:

E_{ext} = the effective dose rate (μSv y^{-1})
T = time being 8766 h y^{-1}
f = the outdoor occupancy factor that corrects for the average time spent outdoors (0.2)
Q = the quotient of the effective dose rate and absorbed dose rate in air (0.7 Sv Gy^{-1})
ε = a factor converting nano (10^{-9}) into micro (10^{-6})
D_{ext} = the absorbed dose rate in air (nGy h^{-1}).

The obtained values are presented in Tables 1 to 4. The average annual outdoor effective dose rates based on the farm soil samples from the areas under consideration were 0.43 ± 0.33 mSv (Bitsichi), 0.24 ± 0.08 mSv (Bukuru), 0.24 ± 0.08 mSv (Ropp) and 0.40 ± 0.26 mSv (Abeokuta). From a radiological point of view, these values are low and do not imply any significant concerns on the health effects on the local population outdoors, as the values are generally not significantly higher than the world average dose equivalents to individuals from soil (0.30 mSv y^{-1}) (Ademola, 2008b).

3.2.3 Radium equivalent

To compare the specific activities of the samples, the radium equivalent activity (Ra_{eq}) can be used as a common index. The radium equivalent provides a useful guideline in regulating the safety standards on radiation protection for the general public. It is the sum of the weighted activities of ^{226}Ra, ^{232}Th and ^{40}K based on the estimation that 10 Bq kg^{-1} of ^{226}Ra, 7 Bq kg^{-1} of ^{232}Th and 130 Bq kg^{-1} of ^{40}K will deliver an equal or the same gamma dose rate (Tufail *et al.*, 2007; Ademola, 2008a–b; Shiva Prasad *et al.*, 2008). The radium equivalent was calculated through the use of the following equation (Tahir *et al.*, 2005; Ahmed and El-Arabi, 2005; Ademola, 2008b):

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K, \tag{4}$$

where A_{Ra}, A_{Th} and A_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Bq kg^{-1}, respectively.

From a radiological and safety limits point of view, the maximum values of the radium equivalent for a material to be used in building construction is $Ra_{eq} \leq 370$ Bq kg^{-1} (UNSCEAR, 1982; Beretka and Mathew, 1985; Tufail *et al.*, 2007). The radium equivalent of 370 Bq kg^{-1} corresponds to the dose limit of 1 mSv for the general population. The use of materials whose radium equivalent concentration exceeds 370 Bq kg^{-1} is discouraged in order to avoid radiation hazards (Sam and Abbas, 2001; Shiva Prasad *et al.*, 2008). Using Equation (4) and the activity concentrations of the radionuclides in Tables 1 to 4, the radium equivalent concentrations were calculated and the results are presented in Table 5 for the areas. As can be seen from Table 5, the average values of the radium equivalent from the areas under investigation were all higher than the recommended limit of 370 Bq kg^{-1} except in Abeokuta. Observe that the high activity concentrations of ^{228}Th and ^{226}Ra in a few farms have a significant effect on the average values of the radium equivalent and the subsequent hazard parameters generally estimated in this work. As mentioned earlier for Bitsichi, where the farm soil has traces of tin tailings, the radium equivalent of the tin tailings recently estimated by Ademola (2008b) ranged between 92.7×10^2 and 84.4×10^3 Bq kg^{-1}.

Table 5 The range and mean of the radium equivalent in Bq kg^{-1}, external hazard index, internal hazard index and gamma index of the farm soil from the areas

Locations	Ra_{eq}	H_{ex}	H_{in}	I_γ
Bitsichi				
Range	199–3603	0.5–9.7*	0.6–11.0	1.4–25.1*
Mean	758	2.0	2.5	5.3
Std. deviation	583	1.6	1.8	4.0
Bukuru				
Range	115–599	0.3–1.6	0.5–2.0	0.9–6.4
Mean	413	1.1	1.4	3.3
Std. deviation	131	0.4	0.4	1.2
Ropp				
Range	228–783	0.6–2.1	0.8–2.6	1.7–5.5
Mean	420	1.1	1.5	3.1
Std. deviation	143	0.4	0.6	1.0
Abeokuta				
Range	51–1236	0.1–3.3	0.2–3.4	0.3–8.8
Mean	357	1.0	1.2	2.6
Std. deviation	303	0.8	0.8	1.9

Note: * Extraneous values due to traces of tin tailings in the farm soil.

3.2.4 *External hazard index*

The external hazard index (H_{ex}) is an important criterion used to assess the radiological suitability of a material for building purposes. The external hazard index due to natural gamma radiation was calculated using the relation (Yang *et al.*, 2005):

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810}, \quad (5)$$

where A_{Ra}, A_{Th} and A_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Bq kg^{-1}, respectively.

The external hazard index is obtained from the expression for the radium equivalent through the supposition that its maximum allowed value corresponds to the upper limit of Ra_{eq} (370 Bq kg^{-1}) ($H_{ex} = \frac{Ra_{eq}}{370}$) so that the annual external dose rate does not exceed 1.5 mGy. To limit the external gamma dose for materials to 1.5 mGy y^{-1} for the radiation hazard to be negligible, the external hazard index should conform with the criterion of $H_{ex} \leq 1$. The H_{ex} values are presented in Table 5. As could be seen, the highest average of 2.0 ± 1.6 was obtained in Bitsichi and the lowest, in Abeokuta with a value of 1.0 ± 0.8.

3.2.5 Internal hazard index

In addition to the external hazard index, there is also a threat to the respiratory organs due to ^{222}Rn, the gaseous short-lived decay product of ^{226}Ra. The internal hazard index (H_{in}) is defined generally to reduce the maximum permissible concentration of ^{226}Ra to half the value appropriate for external exposure alone (Shiva Prased *et al.*, 2008). Internal exposure to radon and its progeny products is quantified by estimating the internal hazard index through this equation (Beretka and Mathew, 1985):

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810}, \quad (6)$$

where A_{Ra}, A_{Th} and A_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Bq kg^{-1}, respectively.

If the maximum concentration of ^{226}Ra is half that of the normal acceptable limit, then H_{in} will be less than unity. For safety precautions in the use of materials in the construction of dwellings, the criterion demands that $H_{in} \leq 1$. The estimated values of H_{in} are presented in Table 5 for the areas under investigation. Values of H_{in} were obtained for the areas where they were 20% to 50% higher than the prescribed limit, except for Bitsichi, where it was more than 100%. This can be accounted for by the extraneous radioactivity values in soil from farm 36 and 37.

3.2.6 Gamma index

The gamma index (I_γ) or representative index is a hazard parameter used to correlate the annual dose rate due to the excess external gamma radiation caused by superficial materials. It is used only as screening tool for identifying materials that might become health concerns when used as construction materials (Tufail *et al.*, 2007). The gamma index was calculated as proposed by the European Commission (EC, 1999):

$$I_\gamma = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_K}{3000}, \quad (7)$$

where A_{Ra}, A_{Th} and A_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Bq kg^{-1}, respectively.

Values of $I_\gamma \leq 1$ correspond to an annual effective dose of less than or equal to 1 mSv, while $I_\gamma \leq 0.5$ corresponds to an annual effective dose less than or equal to 0.3 mSv (Turhan *et al.*, 2008).

3.2.7 Indoor gamma dose rate and the annual effective dose

The indoor gamma dose rate (D_{in}) and the corresponding annual effective dose (E_{in}) due to gamma-ray emissions from the radionuclides (^{226}Ra, ^{232}Th and ^{40}K) in the soil samples as a building material were evaluated using the conversion coefficients and formula provided by UNSCEAR (2000) and the EC (1999) for a standard dimension of $4 \times 5 \times 2.8$ m. The absorbed dose (D_{in}) was calculated using the expression:

$$D_{in}(\text{nGy h}^{-1}) = 0.92 \times A_{Ra} + 1.1 \times A_{Th} + 0.080 \times A_K, \quad (8)$$

where A_{Ra}, A_{Th} and A_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Bq kg^{-1}, respectively. Using the average values of the radionuclide concentrations in Tables 1 to 4 for each area, the average total D_{in} for Bitsichi was 683 nGy h^{-1}, 348 nGy h^{-1} for Ropp, 365 nGy h^{-1} for Bukuru and 295 nGy h^{-1} for Abeokuta. The effective dose rate resulting from the absorbed dose rate values (D_{in}) was calculated using the following relation:

$$E_{in} = T \beta Q D_{in} \varepsilon, \quad (9)$$

where β is the indoor occupancy factor, while other symbols have had their meanings already defined. An indoor occupancy factor of 0.8 was adopted in accordance with UNSCEAR (2000) that 80% of a person's time is spent indoors, on average, around the world. Using Equation (9), the annual effective dose was estimated. The values obtained for Bitsichi was 3.3 mSv, 1.7 mSv for Ropp, 1.8 mSv for Bukuru and 1.5 mSv for Abeokuta. As could be observed, these values are higher than the recommended annual effective dose criterion of 1 mSv by the European Union (EU). This therefore suggests that radiation protection should be given utmost consideration when farm soil from these areas are to be used for the construction of dwellings. As can be seen, the external dose rates and corresponding annual effective dose rate values are quite low, below 1 mSv on average except in a few farms, where values were higher than 1 mSv. When compared with the indoor values, the difference is large. According to Ademola (2008b), an estimated annual gondal dose of 92.4 mSv was obtained for the tin tailings in the Jos Plateau. This, as already highlighted above, contributed to high dose values for Bitsichi when compared with the other areas in Jos Plateau and that of Abeokuta. Generally, therefore, the populations in these areas under investigation are seen as subjects for high radon burden in their dwellings.

4 Conclusion

The study has provided data on the radionuclide concentrations in the farm soil from two high background radiation areas in Nigeria. The results showed that the average values of ^{226}Ra, ^{232}Th and ^{40}K concentrations in Jos Plateau ranged from 109 ± 28 to 163 ± 92 Bq kg^{-1}, 154 ± 56 to 451 ± 368 Bq kg^{-1} and 466 ± 221 to 1062 ± 199 Bq kg^{-1}, respectively. In Abeokuta, the obtained mean activity concentrations for the radionuclides were 65 ± 29 Bq kg^{-1}, 184 ± 205 Bq kg^{-1} and 411 ± 341 Bq kg^{-1} for

^{226}Ra, ^{232}Th and ^{40}K, respectively. The mean total absorbed gamma dose rates varied between 194 ± 59 nGy h^{-1} and 350 ± 270 nGy h^{-1} in Jos Plateau, whereas in Abeokuta, the obtained mean was 167 ± 140 nGy h^{-1}. The average annual outdoor effective dose for the two investigated areas was on average, less than 1 mSv except in some farms, where the values were as high 2 mSv. Assuming that the farm soil is used for construction dwellings in the rural setting, the estimated indoor annual effective doses were greater than 1 mSv. The estimated radiological hazard parameters were, on average, all greater than the safety criterion limits. It generally seems that the populations in the areas might be subjects for high radon burden in their dwellings. Essentially, the two areas showed a geological similarity in terms of the radioactivity distributions of the radionuclides, while extreme values were attributed to traces of tailings in the farm soil in Jos Plateau resulting from past mining activities.

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