

Assessment of Radiological Risks of Chemical Fertilizer Use in Uganda

Bosco Oruru*, Joseph Atine and Gertrude Ayugi

Department of Physics, Makerere University, P. O. Box 7062, Kampala, Uganda.

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Abstract: Modern agriculture relies heavily on fertilizer use to boost crop productivity. In Uganda, agricultural households using chemical fertilizers average 47 kg/acre and 36 kg/acre in the first and second seasons, respectively. While urea and DAP dominate the market, NPK and calcium ammonium nitrate are actively traded. Although chemical fertilizers are essential for agricultural productivity and food security, they may contain radioactive elements - such as thorium and uranium- and their decay products - which may accumulate in soil, crops, and the food chain, posing health risks. In this study, radioactivity levels of chemical fertilizers used in Uganda are determined, and the associated radiological risks assessed. Fertilizer samples have been analyzed using gamma spectrometry – NaI (TI) detector and MAESTRO software utilised. High activity levels of ^{226}Ra , ^{232}Th , and ^{40}K are found in some DAP and NPK samples. The highest mean levels obtained are 67 Bq kg^{-1} (^{226}Ra) and 28 Bq kg^{-1} (^{232}Th) in DAP, and 589 Bq kg^{-1} (^{40}K) in NPK, making ^{226}Ra and ^{40}K exceed the global limits. The absorbed dose is below the global limit of 59 nGy h^{-1} , but the outdoor annual effective dose (in some cases) exceeds the limit of 0.07 mSv y^{-1} . The mean radium equivalent activity is below 370 Bq kg^{-1} , while the internal and external hazard indices are below unity. A strong correlation has been observed between the radiological risk parameters. Although the radiological risk parameters indicate that fertilizer use in Uganda does not pose many health risks, too much use of DAP and NPK can lead to increased radiation exposure to farm workers and the nearby population. Eventually, prolonged exposure may result in radiation-related diseases, for example, cancer.

Keywords: Cancer risk, Radiation dose, Radioactivity, Progeny.

1 Introduction

Extensive use of fertilizers in the agricultural sector has led to an enormous expansion of the global fertilizer industry in recent years. In Uganda, agricultural households using fertilizers applies averagely 46.9 kg per acre and 36.3 kg per acre during the first and second seasons, respectively [1]. The extensive use of fertilizers in agriculture raises concerns about potential contamination by naturally occurring radioactive materials (NORMs), including ^{238}U , ^{232}Th , and ^{40}K . These radionuclides may accumulate in soils, underground water, and crops, posing health risks to humans through prolonged exposure. A study of the influence of NPK fertilizers on the radioactivity of agricultural soils and tobacco plants in Kenya, Tanzania, and Uganda found elevated concentrations of ^{238}U , ^{232}Th , and ^{40}K , respectively [2].

There are two main categories of fertilizers: organic and inorganic fertilizers, which are sourced from different materials and production processes, respectively. Organic fertilizers are derived from natural sources such as plant and animal residues. They improve soil structure and

provide essential nutrients gradually [3]. Inorganic fertilizers are produced through industrial processes. They are also known as chemical or synthetic fertilizers. The primary types of inorganic fertilizers include nitrogen (N) fertilizers, phosphorus (P) fertilizers, and potassium (K) fertilizers, jointly referred to as NPK fertilizers. These are synthesized in different ways [4, 5, 6]. Unlike inorganic fertilizers, organic fertilizers release nutrients slowly, reducing the risk of leaching and environmental contamination [7].

In agriculture, potassium fertilizers enhance soil fertility, but the presence of ^{40}K in them can contribute to increased radioactivity levels in soil and crops. Runoff from potassium-fertilized soils can transport ^{40}K into nearby surface water bodies, leading to contamination of sources of drinking water for both humans and animals. Leaching can also introduce ^{40}K into groundwater systems [8, 9]. Dietary intake by humans can contribute to internal exposure to radiation. Dry and powdered forms of potassium fertilizers can cause airborne dispersion of ^{40}K , hence localized radiation exposure [10]. Farmers and workers handling potassium fertilizers may experience direct exposure through dermal contact and inhalation of

*Corresponding author e-mail: bc.oruru@gmail.com

fertilizer dust, leading to radiation exposure over time [11].

Phosphate fertilizers are manufactured from phosphate rock, which usually contains radionuclides from the natural series of uranium and thorium [12]. The radionuclides may vary in quantity based on the rock origin. For example, phosphate deposits of sedimentary origin contain higher concentrations of ^{238}U and its decay products, with a typical activity concentration of 1500 Bq kg^{-1} [13]. Extraction and processing of phosphate rock lead to redistribution of the radionuclides in the environment, hence elevation in the concentration levels.

Alpha particles and gamma radiation released from radionuclides of the uranium series, thorium series, and potassium are exposed to factory workers who make fertilizers and farmers who use fertilizers [14]. Thus, fertilizers may be one of the causes of increased background radiation. Excessive use of fertilizers can increase radionuclide levels. Evaluation of these radionuclides in fertilizers is crucial for environmental monitoring. Radioactivity levels in chemical fertilizers have been studied elsewhere, and phosphate fertilizers have been found to contain significant levels of ^{238}U and ^{232}Th , with potential environmental implications for tropical agriculture [15, 16, 11, 17, 18, 19].

A study of phosphate rocks in Uganda reported high levels of radionuclides [20], which can draw attention to the safety of fertilizers, given that some fertilizers could be locally manufactured from these rocks, namely Osukuru Hills and Tororo Rock. The primary concerns regarding fertilizers are their potential impact on soil, water, and human health [21]. Human exposure to radionuclides can result in various health hazards, including cancer, genetic mutations, and other radiological illnesses [22]. High doses of radionuclides are associated with lung cancer [23]. This study was justified for Uganda, since agriculture is key in the economic sector [24] and commercial agriculture relies heavily on the use of fertilizers.

Different radionuclides exhibit different decay modes. For example, ^{14}C has beta decay, ^{238}U has alpha decay, ^{232}Th has alpha decay, and ^{40}K has beta decay. Radioactive decay products can emit alpha, beta, or gamma radiation and may undergo further decay processes. Uranium and thorium in phosphate fertilizers can degrade to radium, while radium decays to radon, a radioactive gas [25]. The decay products of radioactive nuclides can be stable or radioactive. Stable decay products are non-radioactive and do not emit ionizing radiation. The decay products of radionuclides can accumulate in the environment and can pose risks to human health and the ecosystem [26].

2 Materials and Methods

2.1 Sample Collection and Preparation

Samples of five fertilizer brands of different origins were collected from agro-input dealers within Kampala. The five fertilizer brands were typically the most common fertilizers used in Uganda, namely: diammonium phosphate (DAP), urea, NPK, calcium ammonium nitrate (CAN), and ammonium sulphate (AS). For purposes of easy coding and identification, single letters D, U, N, C, and A were used to represent the fertilizer brands, respectively. A total of 22 samples were used in the study.

Each of the samples was dried in an oven at approximately $110\text{ }^{\circ}\text{C}$ for 24 hours to remove moisture [27]. The sample was then ground using a mortar and pestle to form fine powder, then sieved through a mesh size of 2 mm to obtain homogeneous particle sizes that minimize analytical variability during radioactivity measurements [28, 29, 30].

About 500 g of each powdered sample was weighed using a digital balance and put in 500 mL standard plastic Marinelli beaker with an airtight seal. The variation of sample weight was kept within $\pm 5\%$ to $\pm 10\%$ to maintain consistent detection efficiency and minimize self-absorption effects [31, 32]. The sample was then kept sealed in the Marinelli beaker for 30 days for secular equilibrium to be reached, that is, when the daughter's rate of decay equals that of the parent [27, 39, 55].

2.2 Determination of Concentrations of Radionuclides

Gamma spectrometric analysis was done using sodium iodide [NaI (Tl)] detector, which was calibrated using the energy peaks of ^{60}Co and ^{137}Cs with known activities and energy peaks [33]. The NaI (Tl) detector is sensitive equipment mounted in a rectangular box with a movable top and surrounded by lead blocks that shield background radiation [34]. Each fertilizer sample, in a Marinelli beaker, was placed on the surface of the NaI (Tl) detector and enclosed with the lead shield. The detector system was then connected to the computer that has the MAESTRO software installed on it. Figure 1 shows the block diagram of the experimental setup.

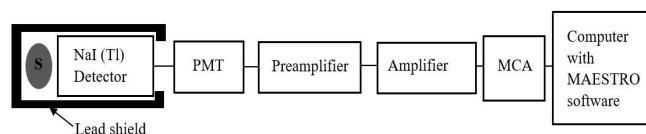


Fig.1: Block diagram of NaI (Tl) detector system and computer.

The mode of operation is as follows. Gamma radiation from the sample strikes the scintillator, causing it to emit visible light photons. Some of these photons enter the photomultiplier tube (PMT) and hit the photocathode, which absorbs the photons and emits electrons. Focusing

electrodes guide the photoelectrons to the first dynode [35]. Accelerated at a pd between 100 V and 300 V, each photoelectron strikes the dynode and emits 2-5 secondary electrons, which in turn are attracted to the next dynode and produce a multiplication of the electrons. By the end of the PMT, the initial signal is multiplied by a factor of a million [36]. The preamplifier boosts the weak signal, which is further amplified to a level suitable for analysis. This signal is then analysed by a multichannel analyser (MCA) and goes into the computer, with MAESTRO software, to display the gamma-ray spectrum.

Analysis was done by comparing each energy peak on the spectrum with the standard energy peaks for numerous radionuclides found in nature. Hence, the radionuclides responsible for the observed energy peaks on the spectra of the sample were identified. A period of 7200 s was used for counting to obtain a clear spectrum.

The wavelength (λ) of gamma radiation can be linked to its energy (E) by Equation 1;

$$E = \frac{hc}{\lambda}, \quad (1)$$

where h is Planck's constant, and c is the speed of light in vacuum [37]. Photons are transmitted according to the Beer-Lambert law; when a monoenergetic gamma-ray beam interacts with electrons, electrical fields, and nuclei of an absorber of thickness x , expressed in Equation 2 [38];

$$I = I_0 e^{-kx}, \quad (2)$$

where I_0 is the intensity of incident radiation, I is the emerging intensity, and k is a measure of the probability of all possible interactions between gamma photons and the atoms of the absorber.

The activity concentrations were calculated using Equation 3 [14];

$$A = \frac{C}{\eta P m t}, \quad (3)$$

where A is the activity in Bq kg^{-1} , C is the net count above the background, η is the efficiency of the detector, P is the emission probability of gamma decay, m is the net mass (kg) of the sample, and t is the measurement time (s).

2.3 Determination of Radiological Risk Parameters

The activity concentrations of the radionuclides were used to determine the radiological risk parameters, namely: absorbed dose, radium equivalent, and hazard indices.

The absorbed dose (D) in nGy h^{-1} due to gamma radiation emitted at 1 m of air above ground was calculated using Equation 4 [27];

$$D = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K, \quad (4)$$

where A_{Ra} , A_{Th} , and A_K are the activities of Ra, Th, and K, respectively, and are preceded by the corresponding absorbed dose rate conversion factors, measured in units of nGy h^{-1} per Bq kg^{-1} [13].

Then, the outdoor annual effective dose (AED_{out}) in mSv was calculated using Equation 5 [20];

$$AED_{out} = D \times P \times R \times Q \times 10^{-4}, \quad (5)$$

where D is the absorbed dose, P is the annual exposure time (taken to be 8760 hours), R is the outdoor occupancy factor 0.2 [13], and Q is the conversion factor from absorbed dose in air to effective dose received by adults (0.7 Sv Gy^{-1}).

The radium equivalent activity (Ra_{eq}) is a parameter that evaluates external exposure. It was obtained using Equation 6 [40];

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K, \quad (6)$$

where the symbols carry the same meanings as defined for Equation 4. The weights are based on the estimation that 370 Bq kg^{-1} of ^{226}Ra , 259 Bq kg^{-1} of ^{232}Th , and 4810 Bq kg^{-1} of ^{40}K produce the same dose [40].

To assess the natural risk of gamma radiation, the external hazard index (H_{ex}) was determined using Equation 7 [41];

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810}. \quad (7)$$

And to provide information on the level of safety from internal exposure due to ^{222}Rn , the internal hazard index (H_{in}) was determined using Equation 8 [42];

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810}. \quad (8)$$

3 Results and Discussion

3.1 Activity Concentrations of Radionuclides

The radionuclides detected in the fertilizer samples were radium, thorium, and potassium, which are radionuclides naturally present in phosphate rocks used in making chemical fertilizers. The activity concentration of ^{226}Ra was

estimated from its decay products: ^{214}Pb (242 keV), ^{214}Pb (295 keV), ^{214}Pb (351.9 keV), and ^{214}Bi (609 keV). Similarly, the activity concentration of ^{232}Th was determined from its decay products: ^{212}Pb (238.6 keV), ^{208}Tl (510.7 keV), ^{208}Tl (583.2 keV), and ^{228}Ac (911.2 keV). The activity concentration of ^{40}K was determined based on its gamma spectrum at 1460.8 keV.

Table 1 shows the activity concentrations determined for each of the samples. Figure 2 shows plots of activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K in DAP fertilizer samples. The activity concentrations of ^{226}Ra varied from 32.89 Bq kg⁻¹ to 116.39 Bq/kg, with the minimum value recorded in sample D1 (Saudi Arabian origin) and the maximum value in sample D4 (Kenyan origin), respectively. The average activity concentration of ^{226}Ra was 67.02 Bq kg⁻¹, which is above the global limit of 35 Bq kg⁻¹.

The activity concentrations of ^{232}Th ranged from 12.09 Bq kg⁻¹ to 50.21 Bq kg⁻¹, with an average of 28.18 Bq kg⁻¹. Only one sample, D3 (German origin), had a higher activity concentration of 50.21 Bq kg⁻¹, above the global permissible level of 35 Bq kg⁻¹. The activity concentrations of ^{40}K varied from 33.31 Bq kg⁻¹ to 238.46 Bq kg⁻¹, with an average of 154.32 Bq kg⁻¹, below the global limit of 400 Bq kg⁻¹.

The DAP fertilizers originate from phosphate rocks, which contain naturally occurring radioactive elements such as uranium and thorium. The concentrations of these radionuclides vary depending on the geological source of the rock [43, 44]. Also, during the production of DAP fertilizers, industrial processes may introduce radioactive contaminants [44]. This may have caused the observed high levels of ^{232}Th in some of the DAP samples.

The activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in Urea and NPK fertilizers are shown in Figures 3 and 4, respectively. Similar trends, as observed and discussed in DAP fertilizers, are observed in Urea and NPK fertilizers.

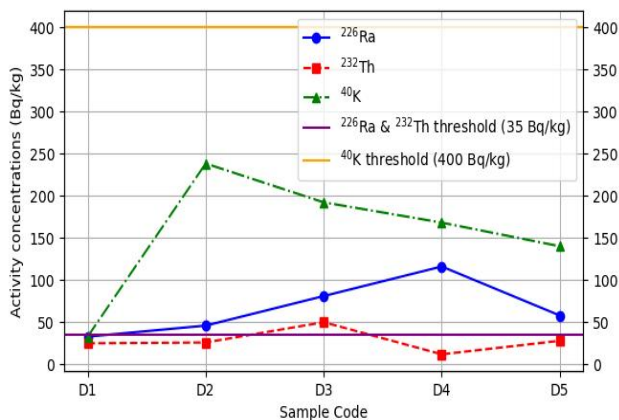


Fig. 2: Activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in DAP fertilizer samples.

Table 1: Activity concentrations (Bq kg⁻¹) of radionuclides in fertilizer samples.

Fertilizer		^{226}Ra	^{232}Th	^{40}K
DAP	D1	32.89 ± 2.22	24.62 ± 1.03	33.31 ± 1.66
	D2	46.13 ± 2.21	25.61 ± 1.09	238.46 ± 4.10
	D3	81.37 ± 3.48	50.21 ± 1.91	192.11 ± 3.68
	D4	116.39 ± 4.15	12.09 ± 0.71	167.74 ± 3.40
	D5	58.30 ± 2.45	28.36 ± 1.36	140.00 ± 2.94
DAP Average		67.02 ± 2.90	28.18 ± 1.22	154.32 ± 3.16
Urea	U1	18.68 ± 0.95	37.29 ± 1.08	195.69 ± 3.47
	U2	7.07 ± 1.78	3.78 ± 0.36	164.42 ± 3.34
	U3	20.60 ± 0.88	27.53 ± 1.04	146.84 ± 3.34
	U4	21.19 ± 1.61	7.97 ± 0.55	132.74 ± 2.80
	U5	12.57 ± 0.77	34.92 ± 1.17	158.39 ± 3.23
Urea Average		17.62 ± 1.20	22.30 ± 0.85	159.62 ± 3.24
NPK	N1	11.48 ± 0.65	68.53 ± 2.65	699.27 ± 6.45
	N2	28.12 ± 1.03	23.30 ± 0.92	458.36 ± 5.32
	N3	17.36 ± 1.20	5.12 ± 0.44	530.30 ± 5.51
	N4	19.14 ± 1.23	9.79 ± 0.69	234.96 ± 3.42
	N5	36.46 ± 2.18	5.09 ± 0.55	282.23 ± 4.62
	N6	67.87 ± 2.94	2.44 ± 0.34	524.43 ± 5.47
	N7	8.38 ± 0.54	41.66 ± 1.39	1395.22 ± 8.58
NPK Average		26.97 ± 1.39	22.28 ± 0.97	589.26 ± 5.62
CAN	C1	46.56 ± 2.32	4.30 ± 0.40	159.87 ± 3.36
	C2	7.08 ± 0.52	6.12 ± 0.46	159.98 ± 3.47
	C3	14.55 ± 1.26	20.56 ± 2.65	130.19 ± 3.23
CAN Average		22.73 ± 1.36	10.33 ± 1.17	150.01 ± 3.35
AS	A1	5.03 ± 0.62	1.78 ± 0.26	77.94 ± 2.33
	A2	15.39 ± 0.77	2.79 ± 0.35	124.52 ± 3.21
AS Average		10.21 ± 0.7	2.29 ± 0.30	101.23 ± 2.77

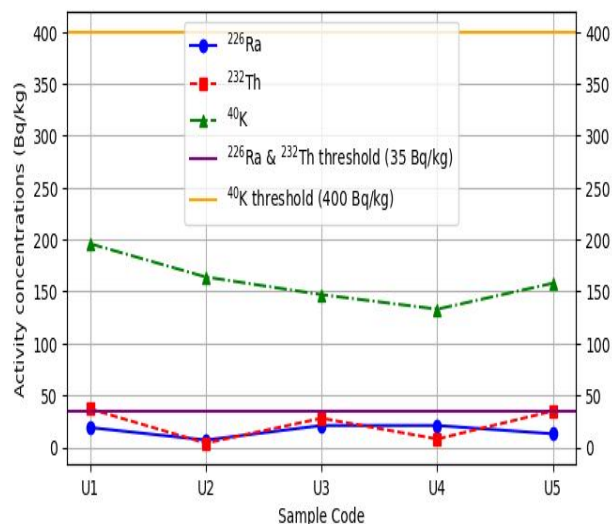


Fig. 3: Activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in Urea fertilizer samples.

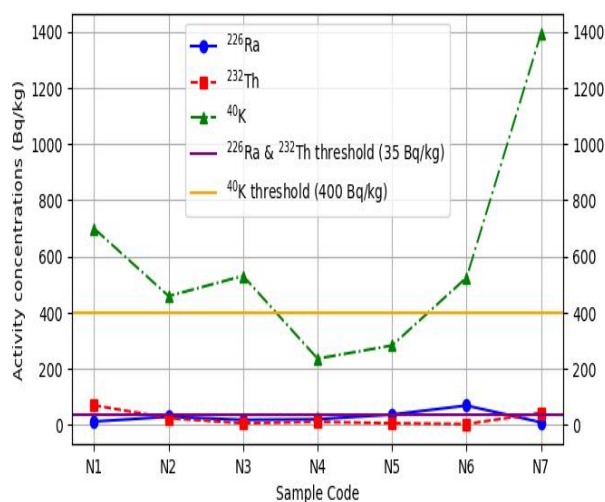


Fig. 4: Activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in NPK fertilizer samples.

Figures 5, 6 and 7 show the mean activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in the five fertilizer brands. The mean activity concentrations of ^{226}Ra , namely 17.62 Bq kg^{-1} in Urea, 26.97 Bq kg^{-1} in NPK, 22.73 Bq kg^{-1} in CAN, and 10.21 Bq kg^{-1} in AS, are below the global average of 35 Bq kg^{-1} .

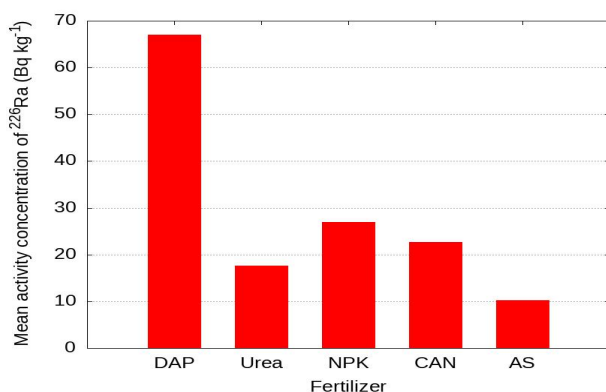


Fig. 5: Average activity concentrations of ^{226}Ra in the fertilizers.

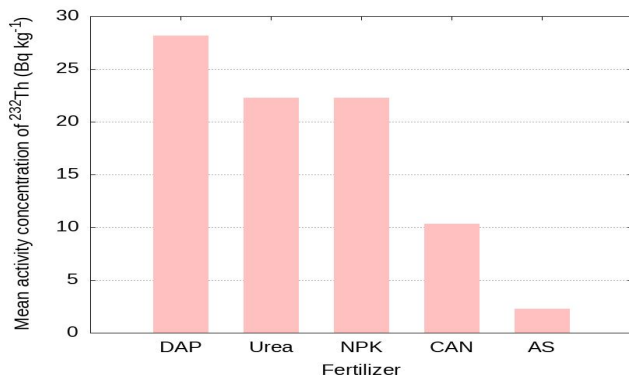


Fig. 6: Average activity concentrations of ^{232}Th in the fertilizers.

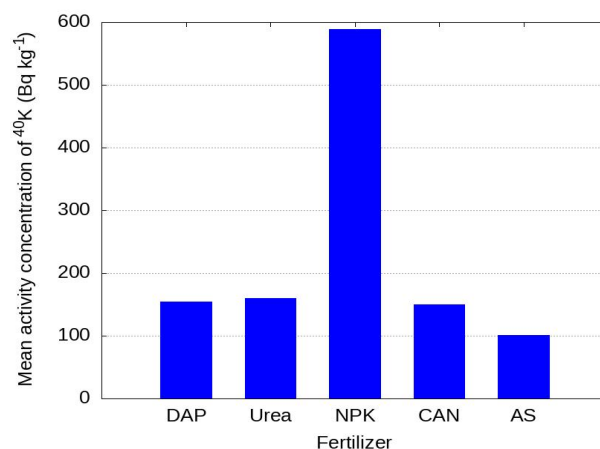


Fig. 7: Average activity concentrations of ^{40}K in the fertilizers.

The DAP fertilizer exhibits a higher mean activity level of 67.02 Bq kg^{-1} . Phosphate fertilizers, mainly derived from phosphate rocks, often contain elevated levels of natural radionuclides such as ^{226}Ra . Findings by other researchers also show that activity concentrations of ^{226}Ra in chemical fertilizers vary, with high values in DAP [45, 46, 47].

The average activity concentrations of ^{232}Th in the fertilizer brands are below the global limit of 35 Bq kg^{-1} , with DAP fertilizers exhibiting the highest average of 28.18 Bq kg^{-1} and ammonium sulphate fertilizers the lowest at 2.29 Bq kg^{-1} . Similarly, the mean activity concentrations of ^{40}K in all fertilizer brands are within the globally acceptable limit of 400 Bq kg^{-1} , except NPK fertilizers with an average of $589.26 \text{ Bq kg}^{-1}$. Potassium is commonly sourced from potash ores, such as potassium chloride (KCl) and potassium sulphate (K_2SO_4). Variations in the potassium content of potash ores can affect the potassium concentration in NPK fertilizers, which can result in high radioactivity levels of ^{40}K in NPK fertilizers [48]. Ammonium sulphate fertilizers present the lowest average activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K , for all fertilizer brands.

3.2 Radiological Risk Parameters

Radiological risk parameters considered in this study are: external absorbed dose (D), annual effective dose (AED), radium equivalent (R_{eq}) activity, and hazard indices. Tables 2 and 3 show radiological risk parameters determined for the fertilizer samples. All these parameters vary greatly, just like the activity concentrations.

Table 2: Radiological risk parameters of fertilizer samples (absorbed dose, annual effective dose, and radium equivalent).

Sample		<i>D</i> (nGy/h)	<i>AED</i> (mSv)	<i>Ra_{eq}</i> (Bq/kg)
DAP	D1	31.46 ± 1.72	0.039 ± 0.002	70.66 ± 3.82
	D2	46.72 ± 1.85	0.057 ± 0.002	101.11 ±
	D3	75.93 ± 2.91	0.093 ± 0.003	4.08
	D4	68.07 ± 2.49	0.083 ± 0.002	167.95 ±
	D5	49.91 ± 2.08	0.061 ± 0.003	6.49
DAP Average		54.42 ± 2.21	0.067 ± 0.003	119.19 ± 4.89
Urea	U1	39.31 ± 1.23	0.048 ± 0.002	87.07 ± 2.75
	U2	12.40 ± 1.18	0.015 ± 0.001	25.13 ± 2.55
	U3	32.27 ± 1.17	0.040 ± 0.001	71.27 ± 2.62
	U4	20.14 ± 1.19	0.025 ± 0.001	42.80 ± 2.60
	U5	33.50 ± 1.19	0.041 ± 0.001	74.71 ± 2.69
Urea Average		28.27 ± 1.20	0.035 ± 0.001	61.80 ± 2.66
NPK	N1	75.86 ± 2.17	0.093 ± 0.002	163.33 ±
	N2	46.18 ± 1.11	0.057 ± 0.001	4.93
	N3	33.23 ± 1.05	0.041 ± 0.001	96.74 ± 2.75
	N4	24.56 ± 1.12	0.030 ± 0.001	65.51 ± 2.26
	N5	31.68 ± 1.49	0.039 ± 0.002	51.24 ± 2.47
	N6	54.70 ± 1.79	0.067 ± 0.002	65.46 ± 3.22
	N7	87.22 ± 1.45	0.11 ± 0.002	111.74 ± 3.85
NPK Average		50.49 ± 1.47	0.062 ± 0.002	104.20 ± 3.22
CAN	C1	30.78 ± 1.46	0.038 ± 0.002	65.02 ± 3.16
	C2	13.64 ± 0.66	0.017 ± 0.001	28.15 ± 1.45
	C3	24.57 ± 2.32	0.030 ± 0.003	53.97 ± 5.30
CAN Average		22.99 ± 1.48	0.028 ± 0.002	49.05 ± 3.30
AS	A1	6.65 ± 0.54	0.008 ± 0.001	13.58 ± 1.17
	A2	13.99 ± 0.70	0.017 ± 0.001	28.97 ± 1.52
AS Average		10.32 ± 0.62	0.013 ± 0.001	21.27 ± 1.34

Figure 8 shows the mean absorbed doses for the different fertilizers. The highest absorbed dose was realized in diammonium phosphate (DAP) fertilizer, while the lowest dose was recorded in ammonium sulphate (AS) fertilizer. Although the mean absorbed dose of 54.42 nGy h⁻¹ in DAP was below the permissible limit of 59 nGy h⁻¹ [13], samples D3 (German origin) and D4 (Kenyan origin) in Table 2

gave absorbed doses exceeding the acceptable limit of 59 nGy h⁻¹. Phosphate fertilizers can have elevated radioactivity levels due to the presence of naturally occurring radionuclides in phosphate rocks.

This can cause higher values of the absorbed dose.

The annual effective dose is an important metric used in radiation safety to assess the total radiation exposure over a year. Figure 9 shows the mean annual effective doses for the different fertilizers. The maximum mean annual effective dose of 0.07 mSv/y was determined for DAP and a minimum of 0.01 mSv/y for ammonium sulphate fertilizers. Again, samples D3 and D4 exceeded the threshold limit of 0.07 mSv y⁻¹ [13]. The values of annual effective dose in DAP indicate that DAP fertilizers have a significant contribution to radiation exposure compared to other chemical fertilizers, as there are higher levels of naturally occurring radionuclides in DAP fertilizers, which can release radiation into the environment [49].

Table 3: Radiological risk parameters of fertilizer samples (external and internal hazard indices).

Sample		<i>H_{ex}</i>	<i>H_{in}</i>
DAP	D1	0.191 ± 0.010	0.280 ± 0.016
	D2	0.273 ± 0.011	0.398 ± 0.017
	D3	0.454 ± 0.018	0.674 ± 0.027
	D4	0.396 ± 0.015	0.711 ± 0.026
	D5	0.296 ± 0.013	0.454 ± 0.019
DAP Average		0.322 ± 0.013	0.503 ± 0.021
Urea	U1	0.235 ± 0.007	0.286 ± 0.010
	U2	0.068 ± 0.007	0.087 ± 0.012
	U3	0.192 ± 0.007	0.248 ± 0.009
	U4	0.116 ± 0.007	0.173 ± 0.011
	U5	0.202 ± 0.007	0.236 ± 0.009
Urea Average		0.167 ± 0.007	0.215 ± 0.010
NPK	N1	0.441 ± 0.008	0.472 ± 0.015
	N2	0.261 ± 0.007	0.337 ± 0.010
	N3	0.177 ± 0.006	0.224 ± 0.009
	N4	0.138 ± 0.007	0.190 ± 0.010
	N5	0.177 ± 0.009	0.275 ± 0.015
	N6	0.302 ± 0.010	0.485 ± 0.018
	N7	0.474 ± 0.009	0.496 ± 0.010
NPK Average		0.281 ± 0.009	0.354 ± 0.012
CAN	C1	0.176 ± 0.009	0.302 ± 0.015
	C2	0.076 ± 0.004	0.095 ± 0.005
	C3	0.146 ± 0.014	0.185 ± 0.018
CAN Average		0.132 ± 0.009	0.194 ± 0.013
AS	A1	0.037 ± 0.003	0.050 ± 0.005
	A2	0.078 ± 0.004	0.120 ± 0.006
AS Average		0.057 ± 0.004	0.085 ± 0.006

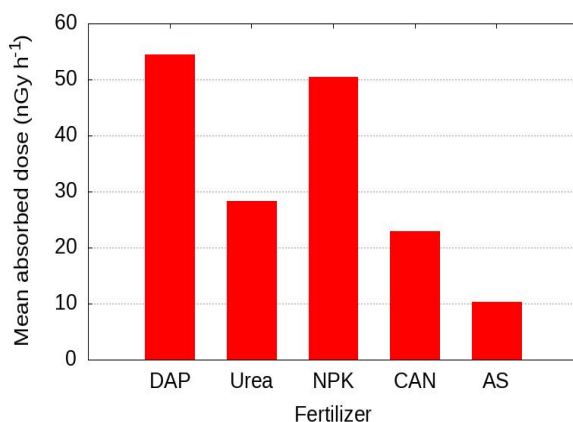


Fig. 8: Mean absorbed dose for chemical fertilizer brands.

The radium equivalent activity is a parameter that represents the combined gamma radiation dose from the radionuclides (²²⁶Ra, ²³²Th, and ⁴⁰K). Figure 10 shows the mean radium equivalent activities for the different fertilizers. Generally, the radium equivalent activities for all the fertilizers are within the global limit of 370 Bq kg⁻¹, suggesting minimal radiological risk [50].

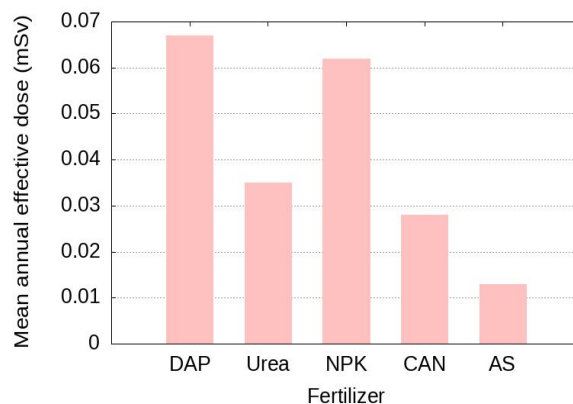


Fig.9: Mean annual effective dose for chemical fertilizer brands.

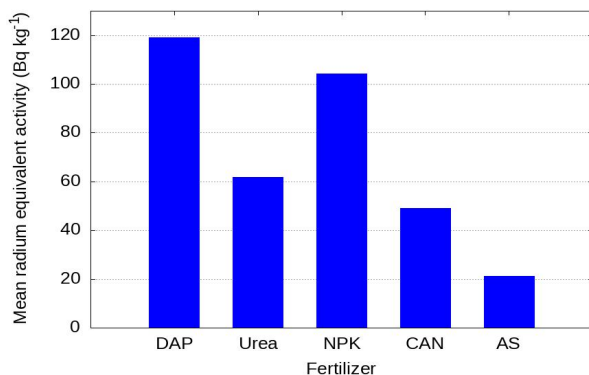


Fig.10: Mean radium equivalent activity for chemical fertilizer brands.

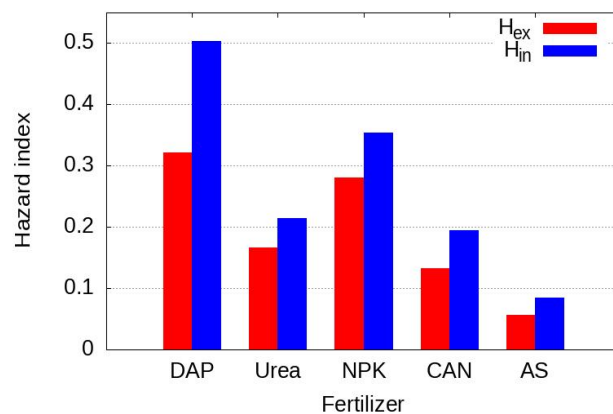


Fig. 11. Mean hazard indices for chemical fertilizer brands.

Figure 11 shows the mean external and internal hazard indices for the different fertilizers. The hazard indices are less than unity, implying an insignificant radiation exposure level. The threshold value of 1 corresponds to the upper limit of 1 mSv y⁻¹ for external gamma radiation dose to the public [51].

The radiological risk parameters of the fertilizers were used to determine Pearson's correlations between them. The Pearson's correlation coefficient is a measure of the strength and direction of the linear relationship between two continuous variables [52]. A strong correlation has a coefficient between 0.5 and 1 [53]. The coefficient (r) was determined using Equation 9 [54];

$$r = \frac{\sum (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum (X_i - \bar{X})^2} \sqrt{\sum (Y_i - \bar{Y})^2}}, \quad (9)$$

X_i and Y_i are data points in X and Y , and $\bar{X}$ and $\bar{Y}$ are the means of X_i and Y_i , respectively. Figures 12 and 13 show the correlations between the radiological risk parameters. Very strong positive correlations exist between the radiological risk parameters.

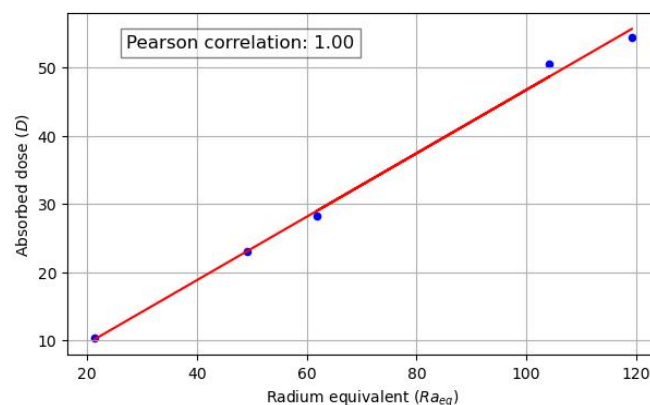


Fig.12: Relationship between radium equivalent activity and absorbed dose.

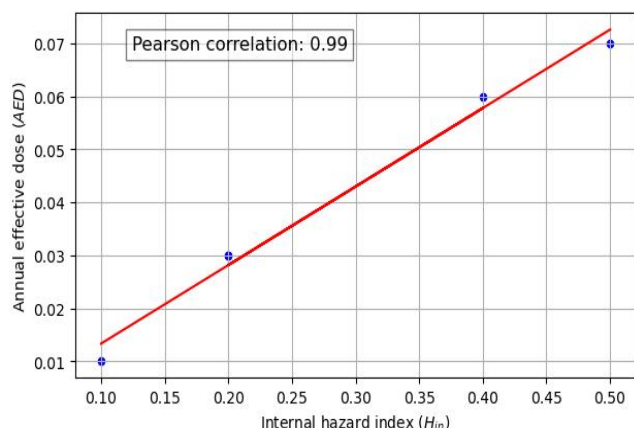


Fig.13: Relationship between internal hazard index and annual effective dose.

Table 4: Pearson's correlation coefficient matrix for the radiological risk parameters in chemical fertilizers.

Code	D	AED	Ra_{eq}	H_{ex}	H_{in}
D	1				
AED	0.993	1			
Ra_{eq}	0.998	0.993	1		
H_{ex}	0.998	0.991	1	1	
H_{in}	0.963	0.979	0.975	0.974	1

Table 4 shows the Pearson's correlation matrix for the radiological risk parameters. The matrix also confirms that very strong positive correlations exist between all the radiological risk parameters, as they are determined from the activity concentrations.

4 Conclusions

Analysis of chemical fertilizers in Uganda has revealed the presence of radionuclides, whose activity concentrations have been estimated from their decay products and gamma spectra. The DAP and NPK fertilizers have shown elevated levels of the radionuclides beyond the globally acceptable limits by UNSCEAR [13], especially ^{226}Ra (37 Bq kg^{-1} above the global limit of 35 Bq kg^{-1}) and ^{40}K (589 Bq kg^{-1} above the global limit of 400 Bq kg^{-1}) for DAP and NPK, respectively. This means that DAP and NPK should be used cautiously or less frequently to avoid increased radiation exposure to farm workers and the nearby population. The radiological risk parameters determined for the fertilizers indicate that fertilizer use in Uganda does not pose many health risks. However, prolonged exposure may result in radiation-related diseases like cancer.

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