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Study of Natural Radioactivity Levels and the Associated Radiological Hazards in Soil from Ambanja City and its Surroundings, Madagascar

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ABSTRACT: The aim of this present work is to investigate the natural radioactivity levels and to estimate the radiological hazards from the soil samples collected from different locations in Ambanja city and its surroundings. In total, twenty soil samples were collected. All samples were oven-dried, sieved, ground and put in appropriate sample container prior to analysis. Sample measurements have been performed by NaI(Tl) gamma spectrometry system with Scintivision software. The mean specific activities of ^{40}K , ^{238}U series and ^{232}Th series were $(730 \pm 141) \text{ Bq.kg}^{-1}$, $(44 \pm 10) \text{ Bq.kg}^{-1}$ and $(123 \pm 14) \text{ Bq.kg}^{-1}$ respectively. These results show that the radioactivity levels of the three natural radionuclides are not uniformly distributed in the soil, and their activities vary from one place to another. These variations can be caused by the interaction with geological formations in the study areas. The mean value of radium equivalent activity in the soil is lower than 370 Bq/kg , meaning that this soil presents no radiological risk when used as a building material. All of the absorbed gamma dose rate is above the worldwide mean value of 57 nGy/h . Regarding the annual effective dose rate, all of these values are below the maximal admissible limit of 1 mSv/year . Thus, there is no significant radiological risk from the soil in this study area.

KEYWORDS: Gamma spectrometry system, specific activity, radium equivalent, absorbed dose, annual effective dose

I. INTRODUCTION

A lot of study about environmental radioactivity levels have been conducted in different region of Madagascar [1-9]. Most of results show that Madagascar locates in the high-level radioactive background [1,2]. Natural radioactivity in the environment has a natural source. Human beings have always been exposed to natural radiation. Most radiation consists of gamma rays, generated mainly by the radioactive decay of unstable nuclei such as ^{238}U series, ^{232}Th series and ^{40}K [1-16]. These radionuclides were widely distributed in important quantities in the soil, but in low quantities in the water, plants, and atmosphere [1-12].

The naturally occurring radioactive elements present in the environment are part of the major problems harmful to human beings and contribute to public radiological exposition. The radiological implication of ^{238}U series, ^{232}Th series and ^{40}K is due to the gamma ray exposure of the human body. In the world, the levels of natural radioactivity vary from one place to another. The dissimilarity in the concentrations of radionuclides present throughout the world is due to the geographical conditions and geological formations [1-4, 6-12].

The aim of this present study is to investigate the natural radioactivity levels and to estimate the radiological risks from the soil samples collected from various locations in Ambanja city and their periphery in Ankatafa, Mahalagony, Ambodimantany countryside.

The present work is very important for the population at the study areas because the natural radioactivity can produce a potential radiological risk from inhalation and ingestion, and can contaminate part of the organ in the human body. Therefore, the data obtained during this research will serve to take preventive measures against the harmful consequences of ionizing radiation on human health, and to create a database for the future study, and then, to initiate the map of the soil radioactivity levels of Ambanja district.

II. MATERIALS AND METHOD

II.1. Description of study sites

This research was carried out in northwest of Madagascar, district of Ambanja, region of DIANA. This study site is located at 1200 km from Antananarivo city, and at 250 km from Antsiranana city. This district is one of the largest cities in the region with about 35,123 inhabitants. Ambanja district is located between four other districts: district of Analalava in the south-west, district of Bealanana in the south-east, district of Nosy-Be in the north-west, district of Ambilobe in the north, and district of Andapa in the east [17,18].



Fig 1: Location of study sites using Laborde coordinates system

The geographical coordinates of this district were ranged from 13°40' 01.80" S to 13°50'01.21" S (latitude) and from 48°31'37.32" E to 48°24'0.23"E (longitude), with an average altitude is about 56m. The district of Ambanja covers a total area of 5,735 km². In general, the minimum and maximum temperatures are 17°C and 33°C respectively during the year with the average value of 26°C. The climate is tropical, characterized by a high temperature and more abundant rainfall. Precipitation and temperature conditions are favorable for tropical tree crops such as cocoa, coffee, vanilla, ylang-ylang as well as food crops and rice crops. The average annual rainfall is 254 mm, characterized by an alternation of a cool and dry season from April to November and a rainy and hot season from December to March [17,18]. This study site is divided in four study areas: Ambanja site, Ankatatafa site, Mahalagny site, and Ambodimantaly site (**Fig 1**).

The geological characteristic of this study area is formed of gneiss and migmatites with quartzites, cipolins and basic gneisses belong to the upper complex of the old Precambrian. This group outcrops in most of the Tsaratanana massif and supports the volcanic formations. This volcanism is stacked by flows and projections reaches a thousand meters thick [17-18].

The soils in this area are mainly of alluvial and hydromorphic types. This alluvium is recent and brought by runoff and deposited on the plains furrowed by the great Sambirano river. This type of soil is rich in mineral elements such as sandy loam, sandy loam and loam clay. These soils are intensively exploited for the industrial cultivation of cocoa, coffee and ylang-ylang. Hydromorphic soils are due to the action of a high-water table, either almost permanently or intermittently on a material of generally alluvial origin. The soil in the Ambanja site is dominated mainly by clay-sandy, fine sandy alluvial soils more clay-loamy, clayey-loamy, fine sandy and sandy-loamy soils. But about Ankatatafa site, the type of soils varies from sandy loam to silty clay. Regarding to Ambodimantaly site, the texture of soils is mainly dark brown, clay loam and lumpy. For Mahalagny site, the soil in this area is the ferrallitic type with clay-silty soil [17-18].

II.2. Sample extraction and preparation method

Fieldwork was carried out in december 2021 at Ambanja, Ankatatafa, Ambodimantaly and Mahalagny sites. The sampling points were identified using an Etrex Garmin brand GPS. All of GPS coordinates obtained were transformed into the Laborde coordinates system. The sampling of the samples made it possible to collect 20 soil samples. The soil characteristics collected and their textures are summarized in **Table 1**. The quantity of a sample taken is approximatively 400 g wet mass, extracted up to 30 cm in depth using a spade. The collected samples were put in plastic bags, labeled and sealed to avoid any kind of contamination.

The soil samples were physically prepared at the Nuclear Analysis and Techniques Department of INSTN-Madagascar. At the laboratory, these samples were steamed at 80°C for 24h to remove moisture, crushed using a mortar and pestle to make them homogeneous and sieved through a 2 mm mesh. And then, the soil sample were put and also sealed hermetically into 200 cm³ cylindrical polyethylene containers for one month to reach secular equilibrium of the ²³⁸U with his daughter decay.

II.3. Gamma spectrometry measurement

The activity concentrations of ²³⁸U series, ²³²Th series and ⁴⁰K were determined using the (3" x3")NaI(Tl) gamma-ray detector (ORTEC, 905-4 series) at the Nuclear Analyses and Techniques Department, (INSTN- Madagascar). The detector energy resolution (FWHM) at 1332.5 keV (for the 60 Co peak) was 7.5%. The detector was shielded into a two-layered stainless steel (10 mm thick) and lead (30 mm thick) in order to minimize the background radiation, as well as the contribution of scattered radiation from the shield [2,19].

II.3.1. Reference materials

The gamma-ray spectrometry system was calibrated for energy and efficiency by using three standard sources (reference materials) such as RGU-1, RGTh-1 and RGK-1, with volume and density characteristics similarly to those of the samples, supplied by the International Atomic Energy Agency (IAEA) so as to ensure the reliability of final results. The uranium standard (RGU-1) is a uranium-ore diluted with silica. RGU-1 has a ²³⁸U activity concentration of (4940 ± 30) Bq.kg⁻¹ and negligible amounts of ⁴⁰K (< 20 ppm) and ²³²Th (< 1 ppm). The thorium standard (RGTh-1) is a thorium-ore diluted with silica. RGTh-1 has a ²³²Th activity concentration of (3250 ± 90) Bq.kg⁻¹ and a ²³⁸U activity concentration of (78 ± 6) Bq.kg⁻¹ but contains a negligible amount of ⁴⁰K (< 0.02 ppm). The potassium standard (RGK-1) is an extra-pure potassium sulphate (99.98%) with (14000 ± 400) Bq.kg⁻¹ of ⁴⁰K, and it has negligible amounts of ²³⁸U (< 0.001 ppm) and ²³²Th (< 0.01 ppm) [20].

II.3.2. Calibration and measurements

All soil samples were counted for 86,400s to reduce statistical uncertainty. Measurements of known masses of samples enabled to determine the activity concentrations of ²³⁸U series, ²³²Th series and ⁴⁰K. The method described by Rybach was used to process the spectra obtained [1,3,6,8]. This method targets three regions of interest corresponding to three isolated intense total absorption peaks of ⁴⁰K (1461 keV), ²¹⁴Bi (1764.5 keV) and ²⁰⁸Tl (2614.5 keV), as shown in Fig 2. The two last radionuclides are progenies of ²³⁸U and ²³²Th series, respectively [1,3,6,8]. The method developed by Rybach was used to calculate the efficiency calibration. Rybach suggested that the width of the regions of interest should be equal to 10% of the energy of the radionuclide [1,3,6,8]. In this study, three regions were exploited and 15% of the energy to recover the entire surface of the entire region peak was took up. Fig 2 illustrates the three regions of interest spanning a range of energy.

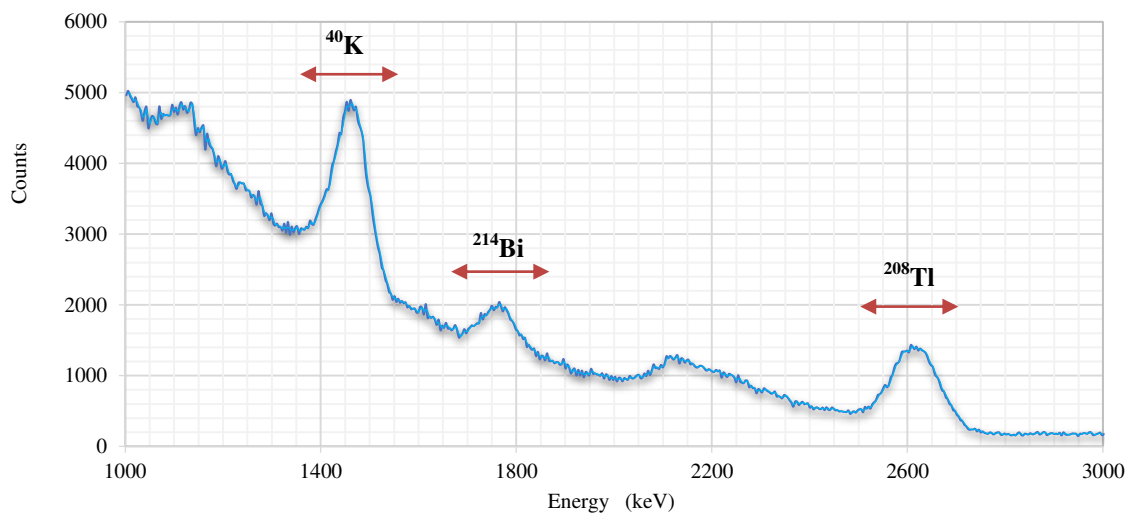


Fig 2. Gamma-ray spectrum of sample and energy windows used to quantify ²³⁸U series, ²³²Th series and ⁴⁰K

II.4. Radionuclide activity concentration measurement

II.4.1. Determination of specific activity concentrations in the soil

To measure the activity concentrations of radionuclide in Bq/kg, for the peak energy E , the following equation system was used:

$$\begin{cases} A_U = a_{2,2}R_U + a_{2,3}R_{Th} \\ A_{Th} = a_{3,2}R_U + a_{3,3}R_{Th} \\ A_K = a_{1,1}R_K + a_{1,2}R_U + a_{1,3}R_{Th} \end{cases} \quad (1)$$

Where A_U, A_{Th} and A_K representing the specific activity concentrations, and R_U, R_{Th} and R_K the recorded net count rates of ²³⁸U series, ²³²Th series and ⁴⁰K respectively. The activity concentration of ²³⁸U series was determined using peak gamma-ray energy of 1764.5 keV (²¹⁴Bi). Similarly, the activity concentration of ²³²Th series was measured using peak gamma-ray energy of 2614.5 keV (²⁰⁸Tl). The activity concentration of ⁴⁰K in a sample was calculated using gamma-ray peak energy of 1461 keV.

II.4.2. Uncertainty for the activity concentrations in the soil

The uncertainties for the ²³⁸U series, ²³²Th series and ⁴⁰K activity concentrations were calculated from the error propagation formula as shown in the equation (2), (3) and (4) respectively:

- Uranium-238 series (²³⁸U series)

$$\sigma_{A_U} = \sqrt{\left(R_U \sigma_{a_{2,2}}\right)^2 + \left(a_{2,2} \sigma_{R_U}\right)^2 + \left(R_{Th} \sigma_{a_{2,3}}\right)^2 + \left(a_{2,3} \sigma_{R_{Th}}\right)^2} \quad (2)$$

- Thorium-232 (²³²Th series)

$$\sigma_{A_{Th}} = \sqrt{(R_U \sigma_{a_{3,2}})^2 + (a_{3,2} \sigma_{R_U})^2 + (R_{Th} \sigma_{a_{3,3}})^2 + (a_{3,3} \sigma_{R_{Th}})^2} \quad (3)$$

- Potassium-40 (⁴⁰K)

$$\sigma_{A_K} = \sqrt{(R_K \sigma_{a_{1,1}})^2 + (a_{1,1} \sigma_{R_K})^2 + (R_U \sigma_{a_{1,2}})^2 + (a_{1,2} \sigma_{R_U})^2 + (R_{Th} \sigma_{a_{1,3}})^2 + (a_{1,3} \sigma_{R_{Th}})^2} \quad (4)$$

II.5. Evaluation of radiation hazard parameters in the soil

II.5.1. Radium equivalent activity

The radium equivalent activity Ra_{eq} is one of the important radiological hazard estimation parameters for the environment. To determinate the radium equivalent activity Ra_{eq} , the following formula in equation (5) was used:

$$Ra_{eq} \text{ (Bq/kg)} = A_U + 1.43A_{Th} + 0.077A_K \quad (5)$$

Where A_U , A_{Th} and A_K are respectively, ²³⁸U series, ²³²Th series and ⁴⁰K activity concentrations. The activity concentrations of 259 Bq/kg of ²³²Th and 4810 Bq/kg of ⁴⁰K are equivalent to 370 Bq/kg of ²²⁶Ra (²³⁸U series). The radium equivalent activity Ra_{eq} corresponds to the combined specific activities of ²³⁸U series, ²³²Th series and ⁴⁰K, and is numerically expressed as an external dose to which the population is exposed. The maximum value of radium equivalent activity should be less than 370 Bq/kg [1,3,6,12,21].

II.5.2. Estimation of absorbed gamma dose rate

The absorbed dose rate D_a in air at 1 m above the ground surface was calculated using equation (6) [1,3,6,12,21]:

$$D_a \text{ (nGy/h)} = 0.462A_U + 0.604A_{Th} + 0.0417A_K \quad (6)$$

The empirical coefficients, 0.462, 0.604, and 0.0417 in equation (6), are air-absorbed dose rate conversion factors (in nGy/h per Bq/kg) at a height of 1 m above the ground for ²²⁶Ra (²³⁸U series), ²³²Th series, and ⁴⁰K, respectively, distributed homogeneously on the ground. This equation has been formulated under the assumption that ²²⁶Ra (²³⁸U) and ²³²Th are in equilibrium with their decay products. The absorbed dose rate reference value is the world average 57 nGy/h [12].

II.5.3. Determination of annual effective dose rate

The annual effective dose rate (AEDR) was calculated from the absorbed dose rate in air (D_a) using the following equation (7) [1,3,6,12,21]:

$$AEDR \text{ (mSv/year)} = D_a \times C_f \times O_f \times T \quad (7)$$

Where D_a is the absorbed dose rate in air, in nGy/h units, C_f denotes the conversion coefficient of 0.7×10^{-6} mSv/nGy (normally reported as 0.7 Sv/Gy) for adults, O_f is the occupancy factor, which for this study was taken to be 0.2 for outdoor occupancy, T is the total of 365.25×24 hours per year (8766h). The annual effective dose from natural sources in normal background areas across the world is estimated to be 1 mSv/year by UNSCEAR 2000 [12].

III. RESULTS

III.1. Radionuclide activity concentrations and radiological parameters in the soil samples from Ambanja, Ankatafa, Mahalagny and Ambodimantaly

The results obtained in this present work were resumed in Table 1. These results show that ²³⁸U series, ²³²Th series, and ⁴⁰K were detected in the soils of the Ambanja city and its surroundings. Therefore, these results were compared into the similar study, carried out in the different district of Madagascar. Table 2 resumes the different average activity value of ²³⁸U series, ²³²Th series, and ⁴⁰K in different district of Madagascar. The variations of activity concentrations

of ²³⁸U series, ²³²Th series, ⁴⁰K, radium equivalent activity, absorbed gamma dose rate and annual effective dose rate were also presented in Fig 3-8 respectively.

Table 1. Specific activities and radiological parameters ± standard errors of ²³⁸U series, ²³²Th series and ⁴⁰K in the soil of Ambanja city and their peripheric

Sample code	Laborde coordinates system		Activity concentrations (Bq.kg ⁻¹)			Radiation hazard parameters		
	Longitude (m)	Latitude (m)	²³⁸ U	²³² Th	⁴⁰ K	Ra _{eq} (Bq/kg)	D _a (nGy/h)	AEDR (mSv/year)
ABJA1	614366.23	1379074.11	39 ± 3	119 ± 6	672 ± 19	261 ± 13	118 ± 6	0.14 ± 0.01
ABJA2	614368.30	1379258.71	29 ± 3	117 ± 6	586 ± 19	241 ± 13	109 ± 6	0.13 ± 0.01
ABJA3	614367.08	1379137.39	29 ± 2	119 ± 6	567 ± 17	243 ± 12	109 ± 5	0.13 ± 0.01
ABJA4	614366.86	1379167.49	50 ± 4	133 ± 7	794 ± 25	301 ± 16	137 ± 7	0.17 ± 0.01
ABJA5	611204.63	1376179.17	53 ± 4	140 ± 7	765 ± 24	312 ± 16	141 ± 7	0.17 ± 0.01
ABJA6	611081.79	1376212.89	37 ± 3	122 ± 6	762 ± 24	270 ± 13	123 ± 6	0.15 ± 0.01
ABJA7	611204.95	1376212.95	45 ± 4	132 ± 7	806 ± 22	296 ± 16	134 ± 7	0.16 ± 0.01
ABJA8	611100.66	1371286.01	47 ± 4	138 ± 7	875 ± 24	312 ± 16	142 ± 7	0.17 ± 0.01
ABJA9	611157.42	1371285.48	53 ± 4	132 ± 7	764 ± 24	301 ± 16	136 ± 7	0.17 ± 0.01
ABJA10	611102.72	1371439.19	44 ± 3	132 ± 7	805 ± 24	295 ± 15	134 ± 7	0.16 ± 0.01
ABJA11	611102.72	1371439.19	47 ± 3	123 ± 6	725 ± 23	279 ± 13	126 ± 6	0.15 ± 0.01
AKTF1	614366.23	1379074.11	39 ± 4	119 ± 7	675 ± 22	261 ± 16	118 ± 7	0.14 ± 0.01
AKTF2	614368.30	1379258.71	47 ± 3	132 ± 7	902 ± 26	305 ± 15	139 ± 7	0.17 ± 0.01
AKTF3	614367.08	1379137.39	72 ± 4	161 ± 7	1065 ± 28	384 ± 16	175 ± 7	0.21 ± 0.01
AKTF4	614366.86	1379167.49	55 ± 5	114 ± 8	912 ± 32	288 ± 19	132 ± 8	0.16 ± 0.01
MHLG1	611204.63	1376179.17	39 ± 3	104 ± 6	465 ± 16	224 ± 13	100 ± 6	0.12 ± 0.01
MHLG2	611081.79	1376212.89	51 ± 3	114 ± 6	642 ± 19	263 ± 13	119 ± 6	0.15 ± 0.01
MHLG3	611204.95	1376212.95	46 ± 5	108 ± 8	540 ± 17	242 ± 18	109 ± 8	0.13 ± 0.01
ABDT1	611100.66	1371286.01	44 ± 4	118 ± 7	654 ± 22	263 ± 16	119 ± 7	0.15 ± 0.01
ABDT2	611157.42	1371285.48	33 ± 4	111 ± 7	694 ± 19	245 ± 15	111 ± 7	0.14 ± 0.01
ABDT3	611102.72	1371439.19	29 ± 3	102 ± 6	655 ± 21	225 ± 13	102 ± 6	0.13 ± 0.01
Mean ±σ [Min – Max]			44 ± 10 [29 - 72]	123 ± 14 [102 - 161]	730 ± 141 [465 - 1065]	277 ± 37 [224 - 384]	125 ± 17 [100 - 175]	0.15 ± 0.02 [0.12 – 0.21]
Reference value			35	30	400	370	57	1

ABJA: Ambanja; AKTF: Ankatafa; MHLG: Mahalagny; ABDT: Ambodimantaly; σ: standard deviation

Table 2. Comparison of similar study of natural radioactivity in the soil samples from different district of Madagascar

District	Average specific activity in soil from Madagascar			References
	²³⁸ U	²³² Th	⁴⁰ K	
Ambanja and their peripheric	44	123	730	Present wok
Antananarivo	14	75	488	[1]
Fort-Dauphin	299	1827	420	[1]
Antsirabe (Vinaninkarena)	176	126	467	[1]
Andranomanelatra	117	149	-	[1]
Antsiranana II (Amber Mountain)	44	90	218	[2]
Antsiranana I (Baie de Français)	139	126	313	[3]
Ambanja (peninsula of Ampasindava)	76	261	355	[4]
Befandriana Nord	21	198	200	[5]

Ambilobe	18	40	518	[6]
Antalaha	34	38	300	[7]

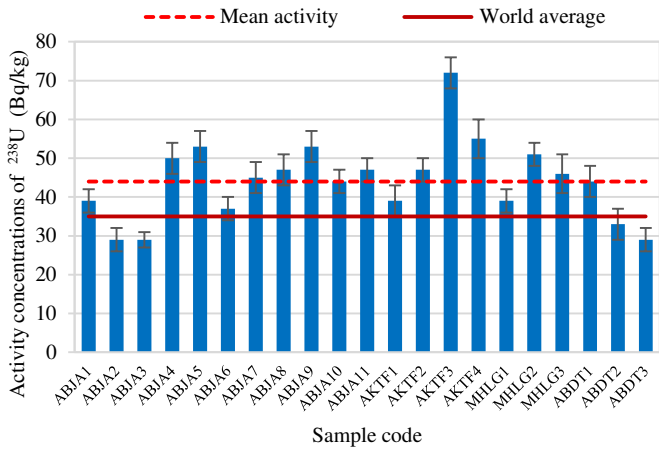


Fig 3. Specific activity of ²³⁸U

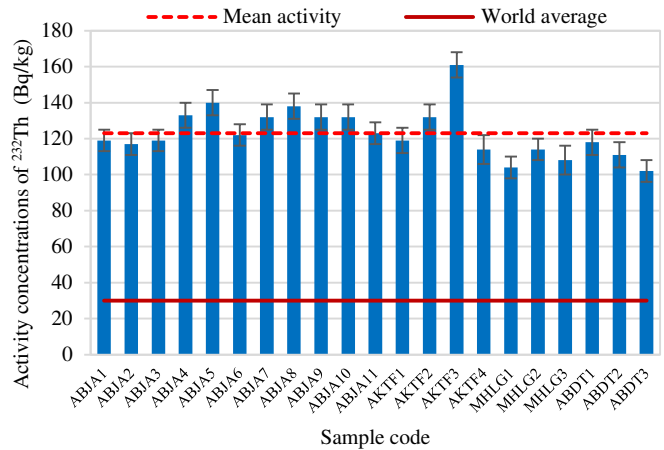


Fig 4. Specific activity of ²³²Th

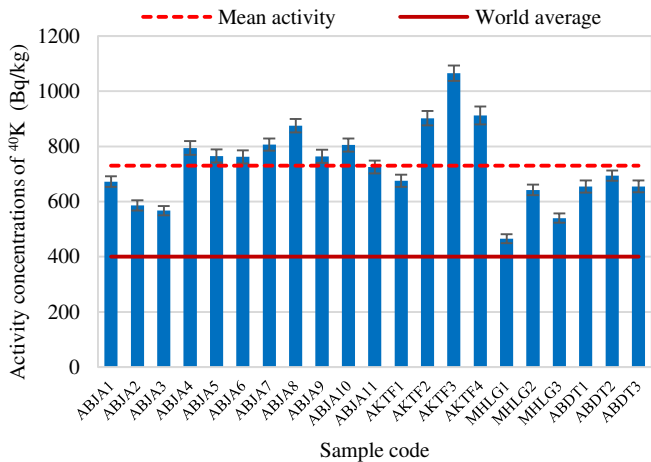


Fig 5. Specific activity of ⁴⁰K

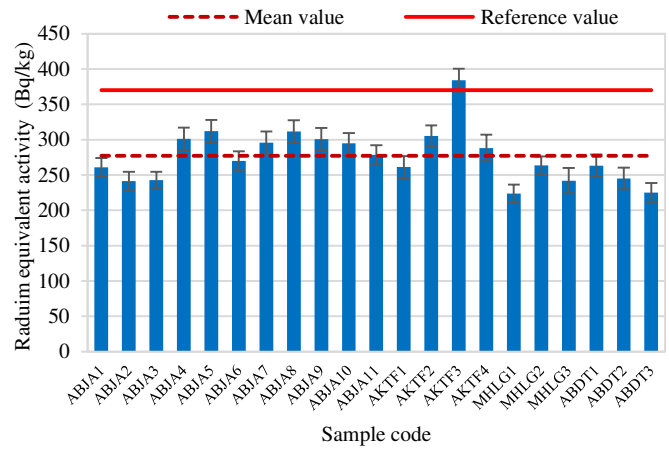


Fig 6. Activity of radium equivalent

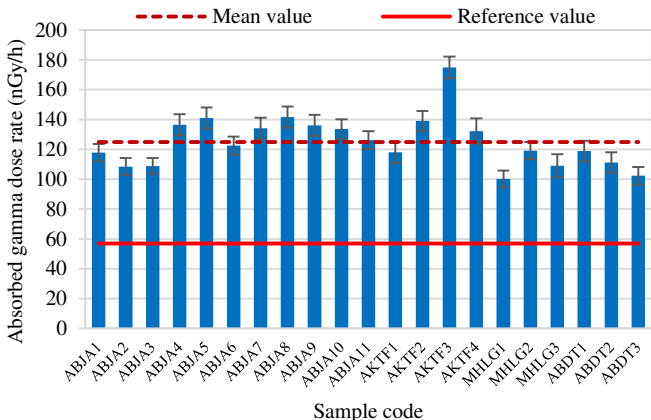


Fig 7. Absorbed gamma dose rate at 1 m above the ground

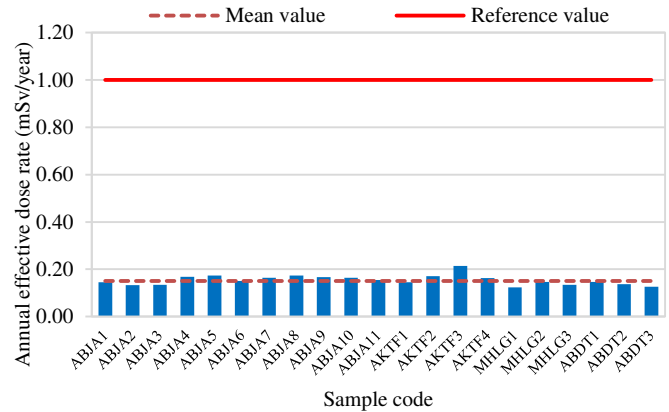


Fig 8. Annual effective dose rate

III.2. Correlations between the different activity concentrations and the radiological parameters

Fig 9 to Fig 23 represent the correlation between the different activity concentrations of ^{238}U series, ^{232}Th series, ^{40}K , and the radiological parameters such as radium equivalent activity, absorbed gamma dose rate and annual effective dose rate.

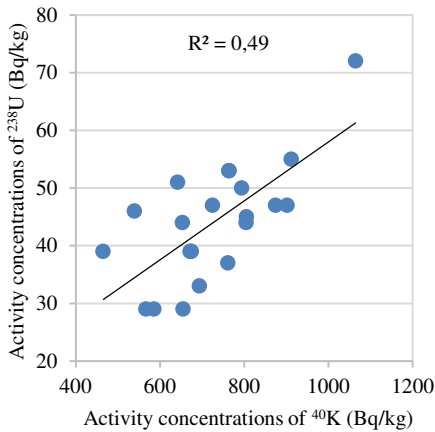


Fig 9. Correlation between $^{40}\text{K}/^{238}\text{U}$

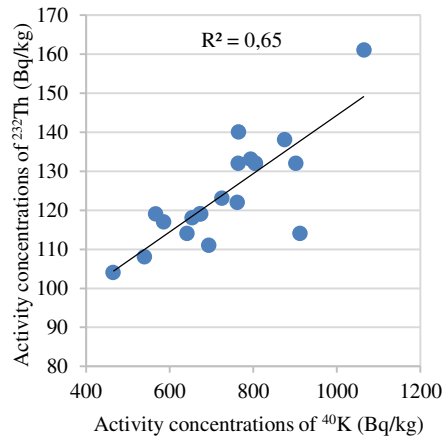


Fig 10. Correlation between $^{40}\text{K}/^{232}\text{Th}$

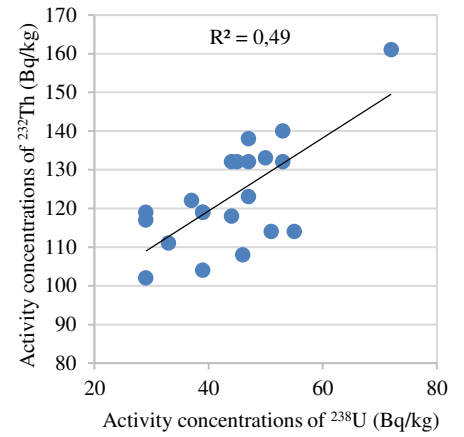


Fig 11. Correlation between $^{238}\text{U}/^{232}\text{Th}$

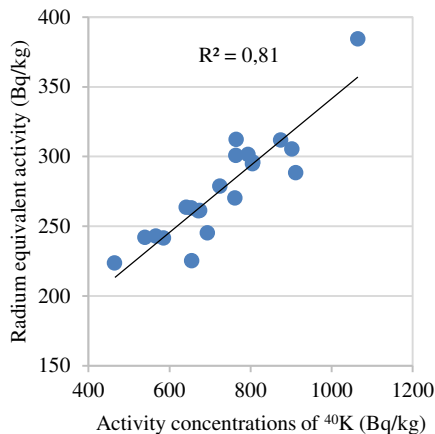


Fig 12. Correlation between $^{40}\text{K}/R_{a_{eq}}$

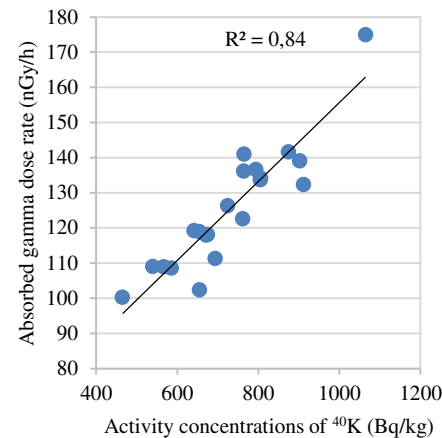


Fig 13. Correlation between $^{40}\text{K}/D_a$

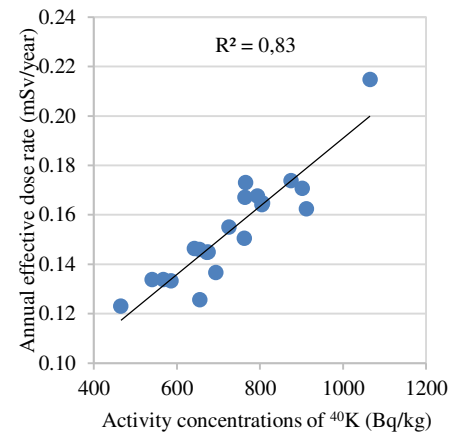


Fig 14. Correlation between $^{40}\text{K}/AEDR$

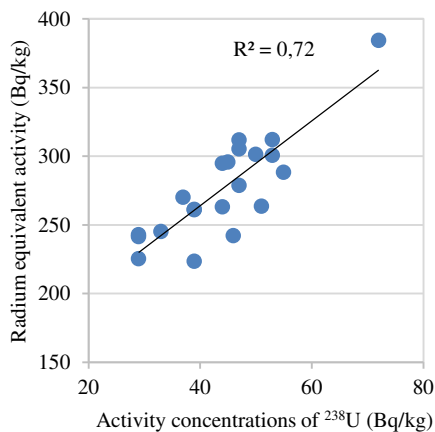


Fig 15. Correlation between $^{238}\text{U}/R_{a_{eq}}$

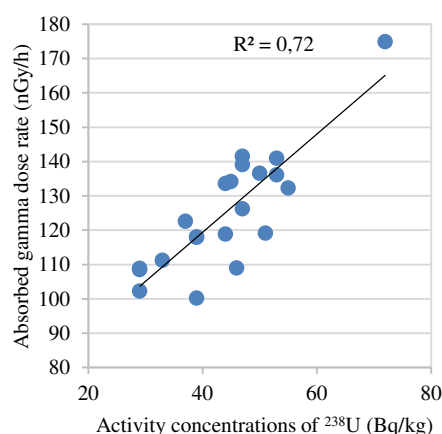


Fig 16. Correlation between $^{238}\text{U}/D_a$

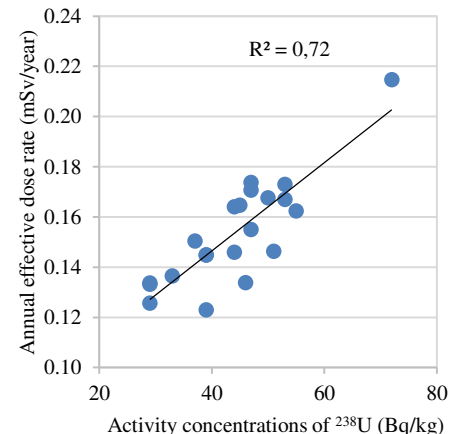


Fig 17. Correlation between $^{238}\text{U}/AEDR$

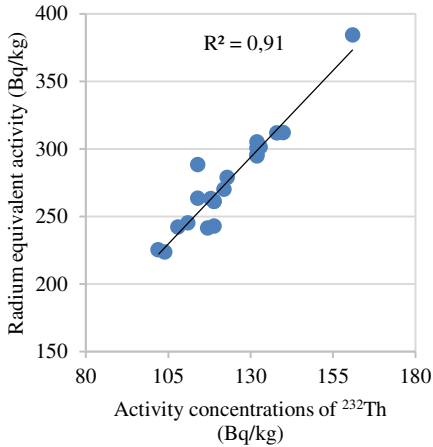


Fig 18. Correlation between $^{232}\text{Th}/Ra_{eq}$

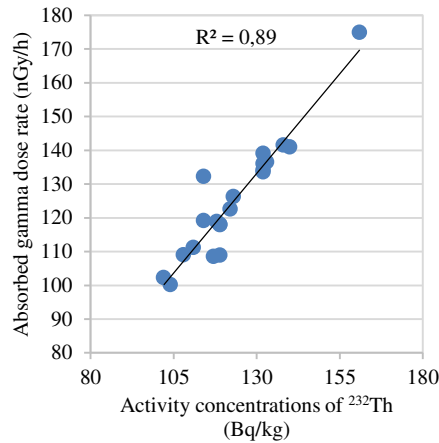


Fig 19. Correlation between $^{232}\text{Th}/Da$

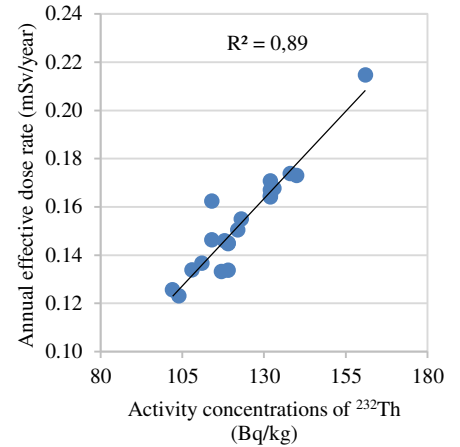


Fig 20. Correlation between $^{232}\text{Th}/AEDR$

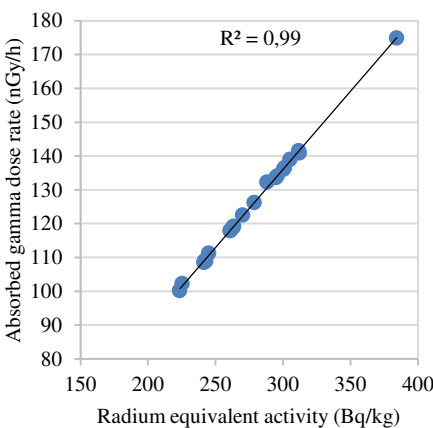


Fig 21. Correlation between Ra_{eq}/Da

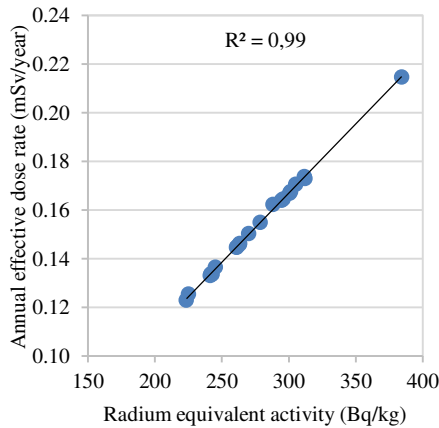


Fig 22. Correlation between $Ra_{eq}/AEDR$

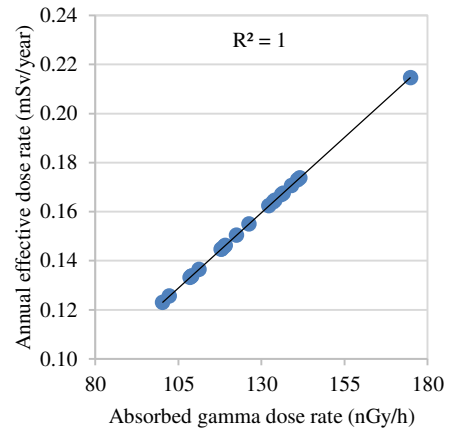


Fig 23. Correlation between $Da/AEDR$

IV. DISCUSSION

The results reveal that ^{238}U series, ^{232}Th series, and ^{40}K were measured in the soil samples from the study sites. The activity concentrations of ^{238}U series ranged from (29 ± 2) to (72 ± 4) Bq/kg with an average of (44 ± 10) Bq/kg. The maximum value of ^{238}U series activity concentration was measured in the sample of Ankatafa site and the minimum was found in the sample of Ambanja and Ambodimantaly sites. The activity concentrations of ^{232}Th series ranged from (102 ± 6) to (161 ± 7) Bq/kg with mean value of (123 ± 14) Bq/kg. The highest value of ^{232}Th series activity concentrations was determined in the sample of Ankatafa site and the lowest was measured in the sample of Ambodimantaly. The activity concentrations of ^{40}K ranged from (465 ± 16) to (1065 ± 28) Bq/kg with an average value of (730 ± 141) Bq/kg. The maximum value of ^{40}K activity concentration was measured in the sample of Ankatafa site and the minimum was found in the sample of Mahalagny. Comparing to the world average value in **Table 1**, the average activity concentrations of ^{238}U series, ^{232}Th series, and ^{40}K in the soil samples collected from this study are much higher than the worldwide average concentrations of 35, 30 and 400 Bq/kg respectively (**Fig 3-5**). All results were compared to the similar study from different district of Madagascar presented in **Table 2**. According to this study, the average activity concentration of ^{238}U series was observed to be slightly higher than the value founded in soil samples from Antananarivo, Befandriana Nord, Ambilobe and Antalaha. On one hand, this value is comparable to the value found in the soil samples from Amber Mountain in Antsiranana II. On the other hand, it is relatively lower than the results obtained in the soil samples from Fort-Dauphin, Antsirabe, Andranomanelatra, Antsiranana I and peninsula of Ampasindava, Ambanja. Regarding the ^{232}Th series, the average activity concentration is much higher compared to the results determined in the soil samples from Antananarivo, Antsiranana II, Ambilobe and Antalaha. Concerning the ^{40}K , the average activity concentration is higher than the values found in the soil samples from different district of

Madagascar (Table 2). The dissimilarity in the activity concentrations of ^{238}U series, ^{232}Th series, and ^{40}K can be explained by the geographical conditions and geological formations of the region of this study sites.

The radium equivalent activity ranged from (224 ± 13) to (384 ± 16) Bq/kg with an average value of (277 ± 37) Bq/kg. According to Fig 6, only one soil sample collected from Ankatafa site has a radium equivalent activity slightly higher than the reference value of 370 Bq/kg. Nevertheless, the average radium equivalent activity calculated in the soil sample from this study is lower compared to the reference value. It means that the soil from this study areas can use as building materials because there presents no significant radiological risk.

Regarding the absorbed gamma dose rate, the dose ranged from (100 ± 6) to (175 ± 7) nGy/h with an average value of (125 ± 17) nGy/h. According to these results, all of the absorbed gamma dose rate values estimated in air at 1 m above the ground surface are higher than the worldwide average value of 57 nGy/h.

In present work, the annual effective dose rates ranged from (0.12 ± 0.01) to (0.21 ± 0.01) mSv/year with an average value of (0.15 ± 0.02) mSv/year. However, all of the annual effective dose rates are relatively lower than the maximal admissible limit of 1 mSv/year proposed by UNSCEAR. Consequently, according to the recommended reference level, it can be observed that there is no significant radiological risk from the soil in this study.

Linear correlation analyses are carried out among the measured of radionuclide activity concentrations and radiological parameters. Their correlations are represented in Fig 9 to Fig 23. The relationships among the activity concentrations and radiological parameters were determined with the Pearson's correlation coefficients. The analysis of the relationships between $^{40}\text{K}/^{238}\text{U}$, $^{40}\text{K}/^{232}\text{Th}$ and $^{238}\text{U}/^{232}\text{Th}$ are moderately correlated with $R^2 = 0.49$, $R^2 = 0.65$ and $R^2 = 0.49$ respectively. However, the strong interaction was observed between $^{40}\text{K}/R_{a_{eq}}$ with $R^2 = 0.81$, $^{40}\text{K}/D_a$ with $R^2 = 0.84$, $^{40}\text{K}/AEDR$ with $R^2 = 0.83$, $^{238}\text{U}/R_{a_{eq}}$ with $R^2 = 0.72$, $^{238}\text{U}/D_a$ with $R^2 = 0.72$, $^{238}\text{U}/AEDR$ with $R^2 = 0.72$, $^{232}\text{Th}/R_{a_{eq}}$ with $R^2 = 0.91$, $^{232}\text{Th}/D_a$ with $R^2 = 0.89$, $^{232}\text{Th}/AEDR$ with $R^2 = 0.89$, $R_{a_{eq}}/D_a$ with $R^2 = 0.99$, $R_{a_{eq}}/AEDR$ with $R^2 = 0.99$ and $D_a/AEDR$ with $R^2 = 1$. According to the results of this correlation analyses, there is significant relationships between the different radionuclides and the radiological parameters in the soil of this study areas.

V. CONCLUSION

Twenty soil samples were collected from Ambanja, Ankatafa, Mahalagny and Ambodimantaly sites. These samples were measured using NaI (Tl) gamma-ray spectrometry. The results show that the ^{238}U series, ^{232}Th series, and ^{40}K were quantified in the soil from the different study sites. The activity concentrations of these natural radionuclides vary from one sampling point to another. The slight variation observed in the radioactivity levels may be due to the non-uniform distribution of the natural radionuclide and to the geological structure and geographical conditions in the study areas. The average activity concentrations of ^{238}U series, ^{232}Th series, and ^{40}K are higher than the worldwide average value recommended by UNSCEAR. The activity concentrations ^{40}K were observed much higher than the values of ^{238}U and ^{232}Th series. According to the results of radiological parameters from this study, it can be concluded that the soil from Ambanja, Ankatafa, Mahalagny and Ambodimantaly may not pose any radiological health risk to the communities in these areas and to the people using this soil for building materials. These results can be used as baseline data for the future investigations of the environmental radioactivity levels in others districts and can be useful for preparing a radioactivity levels map of this region.

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