

Assessment of the Dosimetric Impact and Radiological Risk Associated with Natural Soil Radioactivity in the Antalaha District, Madagascar

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Abstract — The assessment of natural soil radioactivity is essential for the radiological protection of the population. This study evaluates the radiological parameters and associated risks of natural radionuclides (⁴⁰K, ²³⁸U, ²³²Th) in the soils of the Antalaha district, SAVA region Madagascar. Based on the specific activities measured in 50 soil samples, we calculated the absorbed dose rate in air (ADR), the annual effective dose rate (AEDR), and the excess lifetime cancer risk (ELCR). The ADR values range from 22 to 136 nGy·h⁻¹, with a mean of 58 ± 4 nGy·h⁻¹, a value comparable to the worldwide average of 57 nGy·h⁻¹. The mean annual effective dose is 0.177 ± 0.012 mSv·yr⁻¹, which is well below the recommended limit of 1 mSv·yr⁻¹. However, the excess lifetime cancer risk has a mean value of 0.530×10^{-3} , which is higher than the global average of 0.29×10^{-3} , with 42 of the 50 sites exceeding this reference value. Statistical analysis reveals a non-normal distribution of the data, confirming significant spatial variability in radiation levels. Although the annual doses do not create an immediate risk, the long-term cancer risk is higher than the global average, highlighting the importance of continuous monitoring and prudent management of local construction materials.

Keywords— Dosimetric impact, Radiological risk, Absorbed dose, Effective dose, Antalaha, Natural radioactivity.

I. INTRODUCTION

Natural radioactivity, originating mainly from primordial radionuclides such as potassium-40 (⁴⁰K) and the decay chains of uranium-238 (²³⁸U) and thorium-232 (²³²Th), is an inherent component of the terrestrial environment [1-5]. External exposure to gamma radiation emitted by these radionuclides in soil and building materials constitutes the main source of irradiation for the global population [1]. The assessment of this exposure is therefore a major public health issue, particularly in regions where the population has close and prolonged contact with the soil, as is the case in the agricultural areas of Madagascar.

The Antalaha district, located in the SAVA region in northeastern Madagascar, is an economically vital area, renowned for its intensive agriculture, particularly vanilla, and is characterized by a complex geology that combines sedimentary and crystalline formations [6]. This geological diversity suggests a potentially heterogeneous distribution of radionuclides.

In a previous study, an initial investigation of 50 soil samples from this district was conducted by quantifying the specific activities of ⁴⁰K, the ²³⁸U series, and the ²³²Th series [6]. This first study revealed that the specific activities, although variable, were within ranges considered normal and established a preliminary distribution map of these radionuclides. However, quantifying specific activities alone is not sufficient to assess the direct health impact on the local population. It is imperative to translate these activities into concrete dosimetric parameters that measure radiological risk.

The present study is a logical follow-up to our previous work. Building to the specific activity data already published [6], this study aims to fill the gap in dosimetric data for the

Antalaha district. The specific objectives are to: (i) Calculate the absorbed dose rate in air (ADR) at one meter above the ground, (ii) Estimate the annual effective dose rate (AEDR) received by the population, (iii) Assess the excess lifetime cancer risk (ELCR) associated with this exposure, and (iv) Statistically analyze the distribution of these parameters to characterize their variability and identify potential risk areas. This assessment will provide an essential radiological database for the region's health and environmental authorities.

II. MATERIAL AND METHODS

2.1. Study Area Location and Sample Collection

This study was conducted in the Antalaha district, an administrative subdivision of the SAVA region located in northeastern Madagascar. Bordered to the east by the Indian Ocean, the district covers an area of 69092 km² and is home to a population of approximately 220374 inhabitants. Its geographical coordinates range from 14°43'09.41" to 15°59'26.30" South latitude and from 49°50'43.09" to 50°32'07.79" East longitude (Fig. 1) [7].

The selection of this site is justified by its distinctive geological characteristics, which are conducive to variability in natural soil radioactivity. The region's geology is complex, combining an ancient crystalline basement (Precambrian) composed of granites, gabbros, and migmatites with sedimentary and metamorphic formations. These rocks, particularly granites, are known to contain varying concentrations of primordial radionuclides from the ²³⁸U and ²³²Th decay series, as well as ⁴⁰K. Furthermore, the district's soils are predominantly lateritic, resulting from the intense weathering of parent rock under a hot and humid tropical climate. This laterization process can lead to the residual concentration of certain radionuclides. The heterogeneity of the

topography, characterized by coastal plains, hills, and mountainous areas subject to high erosion, suggests an uneven spatial distribution of the terrestrial gamma radiation background. This makes a statistical analysis aimed at identifying potential high-risk areas particularly relevant.

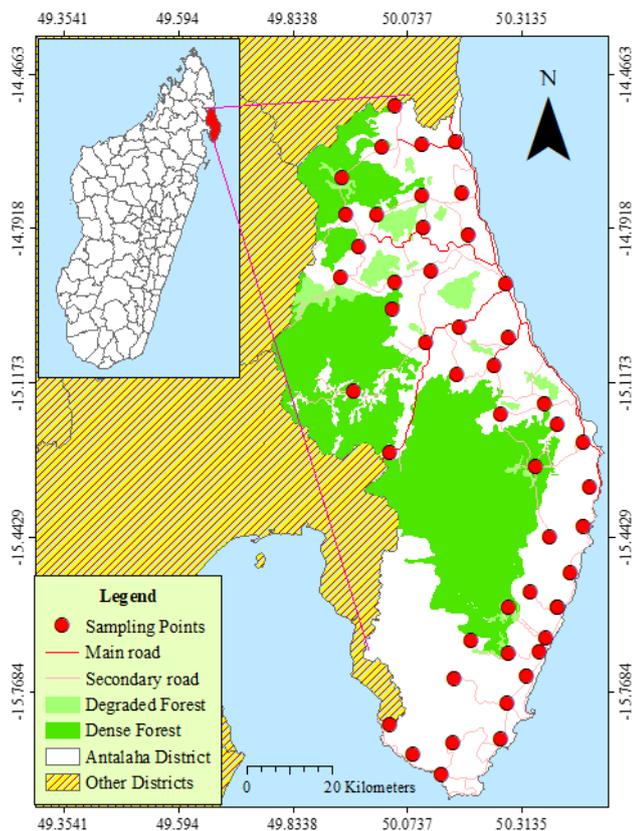


Fig. 1. Location of sampling points

The significance of this assessment is considerably enhanced by the socio-economic profile and lifestyle of the local population. The Antalaha district is predominantly rural, with a large portion of its inhabitants engaged in agricultural activities, notably the cultivation of vanilla, coffee, and cloves on various soil types, such as the rich alluvial soils of the valleys [7]. Consequently, the farming population spends a substantial amount of time outdoors in direct and prolonged contact with the soil. With workdays in the fields typically extending from 6 a.m. to 6 p.m., the outdoor occupancy factor is estimated to be approximately 0.5 (i.e., 50% of the time). This exposure scenario is significantly higher than the standard factors (typically 0.2) used in many risk assessments. It therefore necessitates the precise calculation of the absorbed dose rate in air (ADR), the annual effective dose rate (AEDR), and the excess lifetime cancer risk (ELCR) to obtain a realistic assessment of the health impact on this specific population.

The combination of a geological context favorable to heterogeneous natural radioactivity and a rural lifestyle involving prolonged external exposure makes the Antalaha district a particularly pertinent study site for assessing the dosimetric impact and radiological risks associated with natural soil radioactivity.

Fifty soil samples, each weighing 500 g, were collected from a depth of (0-30 cm) between December 2022 and March 2023, covering various rural and urban communes in the district. The sampling points are illustrated in Fig. 1. The detailed methodology for sampling, preparation (drying, grinding, sieving, weighing), and measurement by gamma spectrometry using a NaI(Tl) detector at the INSTN-Madagascar laboratory has been previously described by Fidelin et al. (2024) in prior work [6].

2.2. Calculation of Radiological Parameters

2.2.1. Absorbed Dose Rates (ADR)

The absorbed dose rate is the fraction of absorbed dose per unit of time. The direct relationship between the concentrations of natural radionuclides and their exposure is known as the absorbed dose rate in air at one meter above the ground. The mean activity concentrations of potassium-40, the uranium-238 and the thorium-232 decay series in the soil samples were used to calculate the absorbed dose rate using the following relation [8-12]:

$$ADR = C_K \times A_K + C_U \times A_U + C_{Th} \times A_{Th} \quad (1)$$

Where A_K , A_U et A_{Th} are the specific activities of ^{40}K , ^{238}U , and ^{232}Th , respectively (in Bq.kg^{-1}); C_K , C_U et C_{Th} are the absorbed dose conversion factors, which are 0.0417, 0.462, and 0.604, respectively, for ^{40}K , ^{238}U , and ^{232}Th as recommended by UNSCEAR (2000).

2.2.2. Annual Effective Dose Rates (AEDR)

The absorbed dose rate in air, measured one meter above the ground, does not directly represent the radiological risk to a person [13]. To estimate this risk, it is necessary to calculate the annual effective dose, which depends on two key parameters: the conversion coefficient from absorbed dose to effective dose and the outdoor occupancy factor. According to international standards from UNSCEAR (2000), the conversion coefficient is 0.7 Sv.Gy^{-1} , and the outdoor occupancy factor is 0.2 (i.e., 20% of time spent outdoors). However, this standard occupancy factor is not applicable to the context of the Antalaha district. The population of Antalaha is predominantly rural and peasant, working in the fields from 6 a.m. to 6 p.m., thus spending nearly 50% of their time outdoors for agricultural activities [14]. Therefore, an occupancy factor of 0.5 was used for this study. The annual effective dose in open air was thus estimated using the following relation [8-12]:

$$AEDR = ADR \times 8766 \text{h} \times 0.5 \times 0.7 \text{ Sv/Gy} \times 10^{-6} \quad (2)$$

Where $AEDR$ is the annual effective dose expressed in mSv.yr^{-1} , ADR is the absorbed dose rate in nGy.h^{-1} , 8766 h is the annual exposure duration, 0.7 Sv.Gy^{-1} is the conversion factor from absorbed dose to effective dose, and 0.5 is the outdoor occupancy factor.

2.2.3. Excess Lifetime Cancer Risk (ELCR)

To determine the excess lifetime cancer risk due to gamma radiation, the following equation is used [15-21]:

$$ELCR = AEDR \times T_v \times R_f \quad (3)$$

Where $ELCR$ is the excess lifetime cancer risk; T_v is the estimated average lifetime (for Madagascar: 60 years) [14], and R_f is the cancer risk factor, valued at 0.05 Sv^{-1} [19, 21-24].

III. RESULTS AND DISCUSSION

The results of the radiological parameters in the soil of the Antalaha district, shown in Table I, were calculated using the specific activities of potassium-40, the uranium-238 family, and the thorium-232 family published by Fidelin et al. (2024) [6].

TABLE I. Values of radiological parameters in the study area

Sample ID	ADR (nGy.h ⁻¹)	AEDR (mSv.yr ⁻¹)	ELCR (×10 ⁻³)
ATLH01	39 ± 5	0.121 ± 0.017	0.363 ± 0.050
ATLH02	52 ± 6	0.161 ± 0.017	0.483 ± 0.052
ATLH03	68 ± 6	0.208 ± 0.017	0.625 ± 0.052
ATLH04	94 ± 6	0.288 ± 0.017	0.864 ± 0.052
ATLH05	48 ± 5	0.146 ± 0.016	0.439 ± 0.048
ATLH06	37 ± 5	0.115 ± 0.016	0.345 ± 0.047
ATLH07	43 ± 5	0.132 ± 0.015	0.396 ± 0.046
ATLH08	47 ± 6	0.146 ± 0.017	0.437 ± 0.052
ATLH09	116 ± 5	0.355 ± 0.017	1.066 ± 0.050
ATLH10	66 ± 4	0.202 ± 0.012	0.606 ± 0.037
ATLH11	84 ± 5	0.257 ± 0.016	0.772 ± 0.049
ATLH12	77 ± 5	0.236 ± 0.017	0.709 ± 0.050
ATLH13	75 ± 5	0.230 ± 0.015	0.691 ± 0.046
ATLH14	80 ± 8	0.245 ± 0.023	0.735 ± 0.069
ATLH15	40 ± 5	0.123 ± 0.015	0.370 ± 0.045
ATLH16	136 ± 11	0.416 ± 0.034	1.248 ± 0.103
ATLH17	75 ± 6	0.231 ± 0.018	0.693 ± 0.055
ATLH18	74 ± 5	0.228 ± 0.017	0.684 ± 0.050
ATLH19	48 ± 5	0.148 ± 0.015	0.445 ± 0.044
ATLH20	61 ± 3	0.187 ± 0.011	0.560 ± 0.032
ATLH21	47 ± 5	0.146 ± 0.014	0.437 ± 0.042
ATLH22	86 ± 7	0.264 ± 0.021	0.792 ± 0.063
ATLH23	61 ± 5	0.188 ± 0.017	0.564 ± 0.050
ATLH24	40 ± 6	0.124 ± 0.019	0.371 ± 0.057
ATLH25	34 ± 4	0.104 ± 0.013	0.311 ± 0.040
ATLH26	76 ± 4	0.233 ± 0.013	0.700 ± 0.038
ATLH27	116 ± 5	0.355 ± 0.015	1.064 ± 0.044
ATLH28	42 ± 5	0.128 ± 0.016	0.383 ± 0.049
ATLH29	45 ± 4	0.138 ± 0.013	0.413 ± 0.038
ATLH30	36 ± 6	0.110 ± 0.018	0.330 ± 0.053
ATLH31	33 ± 4	0.102 ± 0.013	0.306 ± 0.040
ATLH32	81 ± 6	0.247 ± 0.017	0.742 ± 0.051
ATLH33	70 ± 5	0.216 ± 0.016	0.648 ± 0.049
ATLH34	39 ± 5	0.120 ± 0.017	0.360 ± 0.050
ATLH35	23 ± 5	0.070 ± 0.015	0.211 ± 0.044
ATLH36	71 ± 11	0.219 ± 0.032	0.656 ± 0.097
ATLH37	36 ± 7	0.110 ± 0.023	0.331 ± 0.068
ATLH38	23 ± 3	0.070 ± 0.011	0.211 ± 0.032
ATLH39	28 ± 3	0.085 ± 0.010	0.254 ± 0.029
ATLH40	22 ± 4	0.068 ± 0.012	0.205 ± 0.035
ATLH41	123 ± 6	0.378 ± 0.017	1.135 ± 0.052
ATLH42	51 ± 6	0.157 ± 0.017	0.471 ± 0.052
ATLH43	34 ± 4	0.104 ± 0.012	0.311 ± 0.037
ATLH44	48 ± 6	0.147 ± 0.018	0.442 ± 0.053
ATLH45	26 ± 4	0.079 ± 0.012	0.236 ± 0.037
ATLH46	30 ± 5	0.092 ± 0.015	0.276 ± 0.045
ATLH47	78 ± 6	0.241 ± 0.017	0.722 ± 0.051
ATLH48	71 ± 5	0.217 ± 0.016	0.651 ± 0.047
ATLH49	24 ± 4	0.073 ± 0.012	0.219 ± 0.036
ATLH50	22 ± 3	0.068 ± 0.010	0.204 ± 0.030
[Min-Max]	[22 - 136]	[0.068 - 0.416]	[0.204 - 1.248]
Mean ± SEM	58 ± 4	0.177 ± 0.012	0.530 ± 0.036
Reference	57	1	0.29

Based on the results in Table I, it is observed that the ADR values range from 22 ± 3 nGy·h⁻¹ (ATLH50) to 136 ± 11 nGy·h⁻¹ (ATLH16), with a mean of 58 ± 4 nGy·h⁻¹. This mean value is remarkably close to the global average of 57 nGy·h⁻¹

reported by UNSCEAR [1]. However, the wide range of values, visualized in Fig. 2, indicates significant radiological heterogeneity in the district. Some sites, notably ATLH09 (116 nGy·h⁻¹) and ATLH41 (123 nGy·h⁻¹), exhibit radiation levels more than twice the mean, which can be attributed to local geological variations, such as a higher concentration of heavy minerals.

The mean ambient radiation level in the Antalaha district is consistent with global averages, but localized radiological "hotspots" exist and warrant special attention. The AEDR ranges from 0.068 ± 0.010 mSv·yr⁻¹ to 0.416 ± 0.034 mSv·yr⁻¹, with a mean of 0.177 ± 0.012 mSv·yr⁻¹. As shown in Fig. 3, all calculated values are well below the dose limit of 1 mSv·yr⁻¹ recommended for the public by the ICRP [13]. Even the site with the highest dose (ATLH16) corresponds to only about 42% of this limit.

External exposure to terrestrial gamma radiation in the Antalaha district does not pose an immediate radiological risk to the health of the population, as the received doses are significantly lower than regulatory limits.

The ELCR ranges from 0.204 × 10⁻³ to 1.248 × 10⁻³, with a mean of 0.530 × 10⁻³. This is a notable result: this mean value is nearly double the global reference average of 0.29 × 10⁻³ [1]. Furthermore, 42 of the 50 samples (84% of the sites) show an ELCR value higher than this global reference (Fig. 4).

Although the annual doses are low, chronic lifetime exposure to the natural radiation level in the Antalaha district could lead to a slightly higher probability of developing cancer than the global average. This risk, though probabilistic, should not be overlooked.

3.1. Statistical Analysis and Correlations

The descriptive statistical analysis is summarized in Table II. The Shapiro-Wilk test yielded a p-value of 0.002 for all three parameters, which is less than 0.05. This confirms that the data distribution is not normal, but rather right-skewed (skewness > 0).

TABLE II. Statistical distribution of radiological parameters from natural radionuclides

Statistical parameters	Absorbed Dose Rate	Annual Effective Dose	Excess Lifetime Cancer Risk
Number of samples	50	50	50
Mode	48	0.146	0.211
Mean	57.520	0.177	0.530
Std. Error of Mean	3.944	0.012	0.036
Std. Deviation	27.891	0.085	0.256
Skewness	0.912	0.901	0.901
Kurtosis	0.459	0.440	0.438
Minimum	22	0.068	0.204
25th percentile	36.00	0.110	0.331
Median	48.00	0.148	0.444
75th percentile	75.25	0.232	0.695
Maximum	136	0.416	1.248
Shapiro-Wilk Test	0.002	0.002	0.002

The box plots (Fig. 5, 6, and 7) visually illustrate this distribution. It is observed that for each parameter, the mean is greater than the median, which is characteristic of a right-

skewed distribution. The presence of numerous data points above the 75th percentile (upper limit of the "box") confirms the existence of several sites with high radiation values that pull the mean upwards.

Fig. 8, 9, and 10 show the correlations between ADR, AEDR, and ELCR. A correlation coefficient (R^2) closes to 1 is observed in all three cases. This perfect correlation is expected, as AEDR and ELCR are mathematically derived from ADR using constant conversion factors. This validates the coherence of the calculations but does not reflect a geological relationship. We also note that the mean absorbed dose rate (ADR) in the present study is $58 \text{ nGy}\cdot\text{h}^{-1}$. On a national scale, this result is identical to that measured in the Ambilobe district ($58 \text{ nGy}\cdot\text{h}^{-1}$) [4], but significantly lower than that of Ambanja ($125 \text{ nGy}\cdot\text{h}^{-1}$) [5], a region with a particular geology. Internationally, this

value is higher than those in Egypt ($32 \text{ nGy}\cdot\text{h}^{-1}$) and the United States ($47 \text{ nGy}\cdot\text{h}^{-1}$), but lower than that in Malaysia ($92 \text{ nGy}\cdot\text{h}^{-1}$) [1].

Regarding the excess lifetime cancer risk (ELCR), the mean value of this study (0.530×10^{-3}) is comparable to that of Ambilobe (0.50×10^{-3}) [4]. However, it is higher than the values reported in Iraq (0.36×10^{-3}) and Armenia (0.27×10^{-3}) [9, 25].

This analysis makes the Antalaha district as an area where the long-term radiological risk is slightly higher than the global average and that of other regions. This elevated ELCR is explained by the relatively high specific activity of thorium and potassium in the district's soils, a fact already demonstrated in our previous study [6].

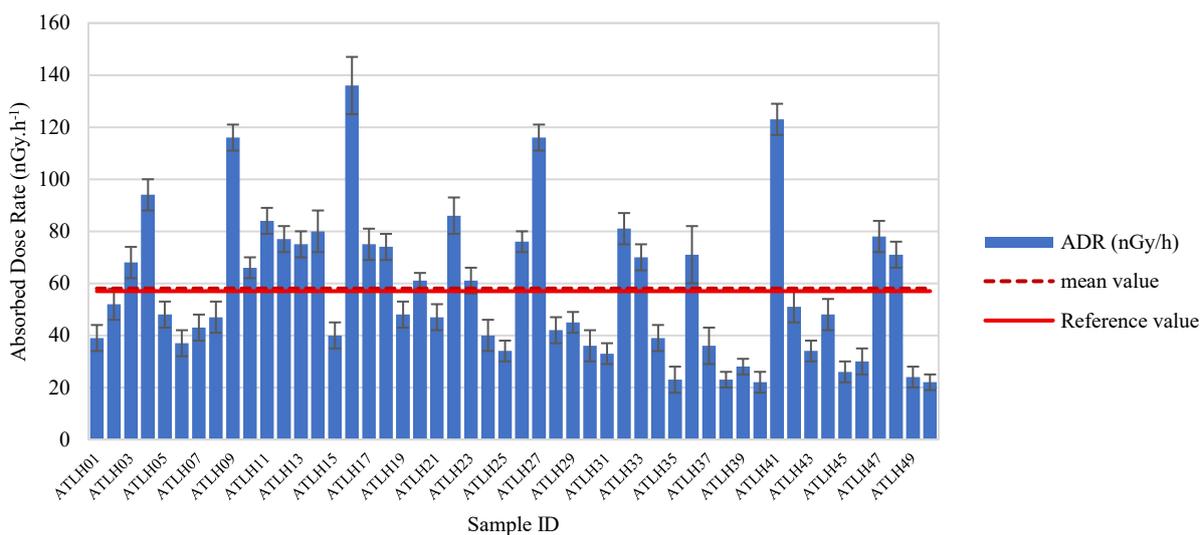


Fig. 2. Variation of Absorbed Dose Rate ($\text{nGy}\cdot\text{h}^{-1}$) in soil of Antalaha District

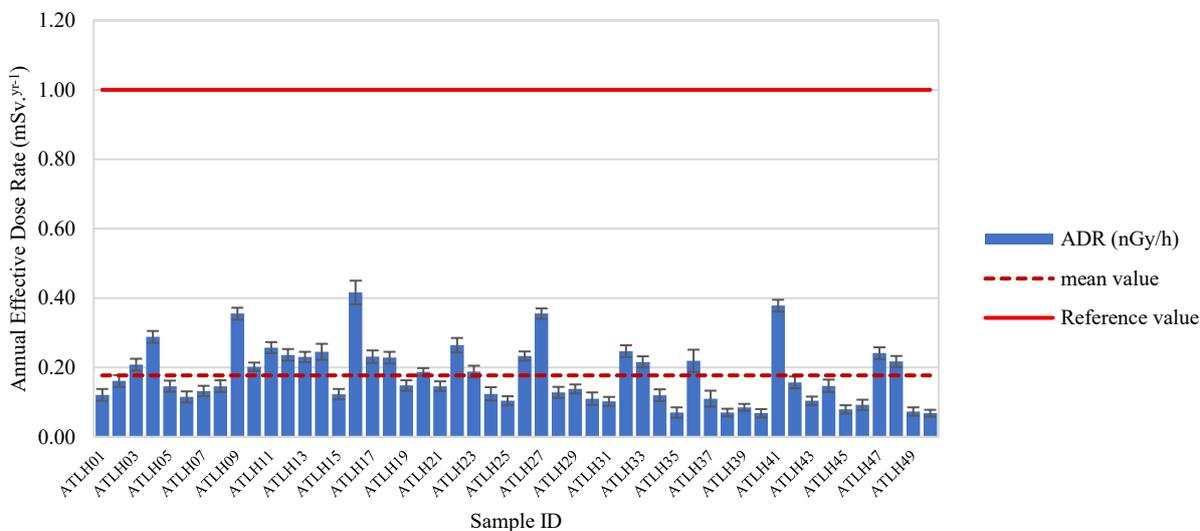


Fig. 3. Variation of Annual Effective Dose Rate ($\text{mSv}\cdot\text{yr}^{-1}$) in soil of Antalaha District

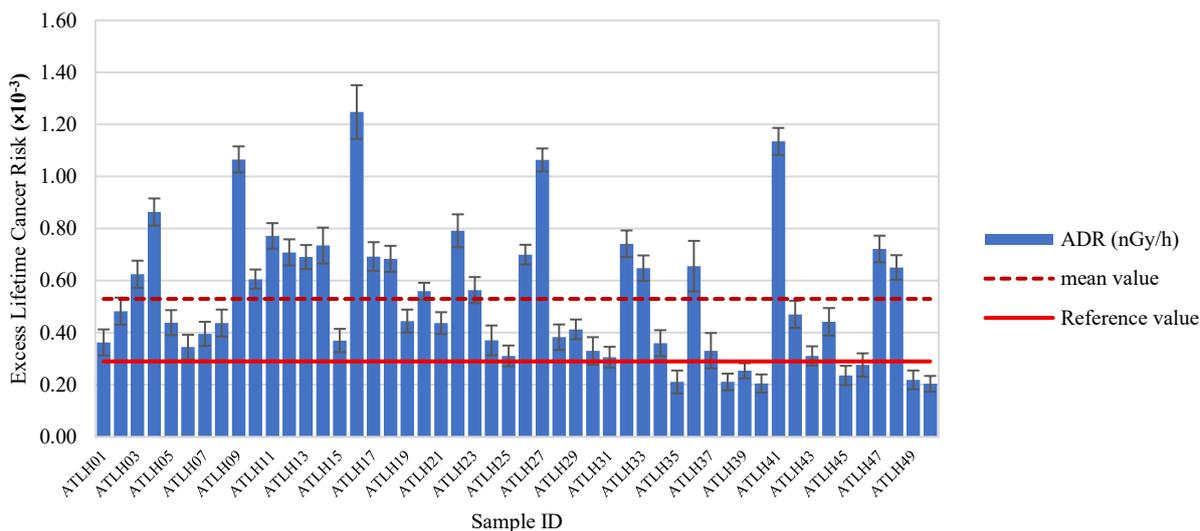


Fig. 4. Variation of Excess Lifetime Cancer Risk ($\times 10^{-3}$) in soil of Antalaha District

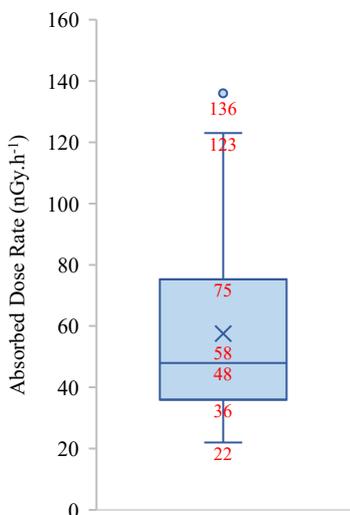


Fig. 5. Box plot of ADR

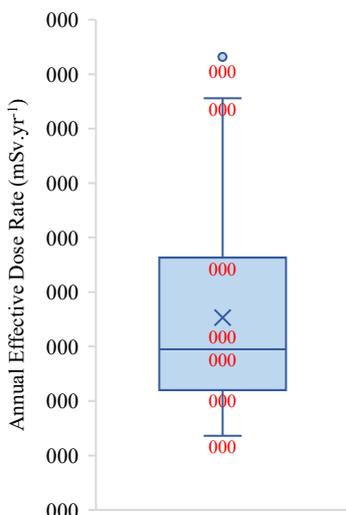


Fig. 6. Box plot of AEDR

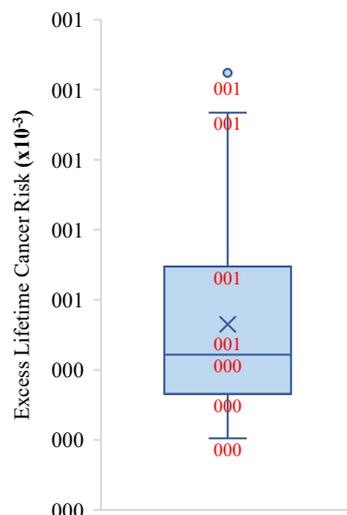


Fig. 7. Box plot of ELCR

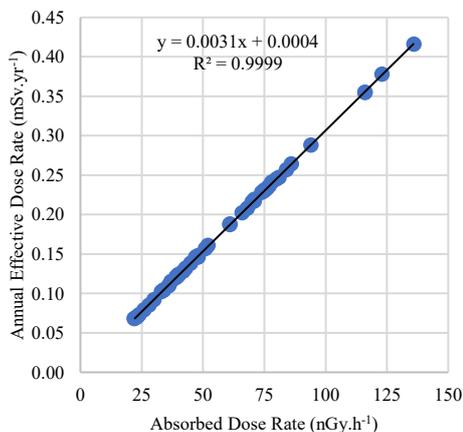


Fig. 8. Correlation between ADR and AEDR

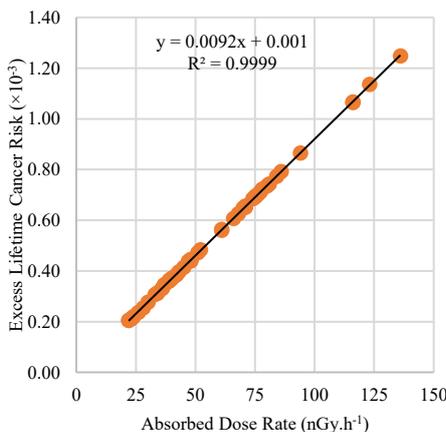


Fig. 9. Correlation between ADR and ELCR

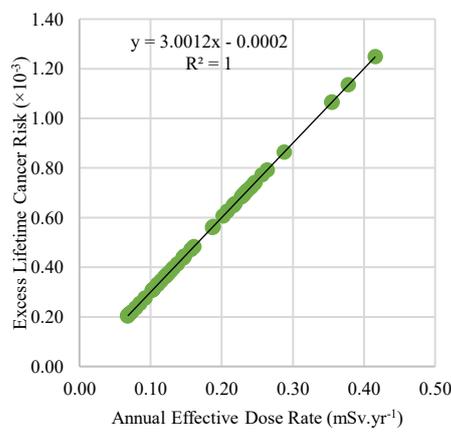


Fig. 10. Correlation between AEDR and ELCR

IV. CONCLUSION

This study has, for the first time, quantified the dosimetric impact and radiological risk associated with natural radioactivity in the soils of the Antalaha district. The main findings are as follows:

- The mean absorbed dose rate ($58 \text{ nGy}\cdot\text{h}^{-1}$) is consistent with the global average but exhibits high spatial variability with areas of higher radiation.
- The mean annual effective dose rate ($0.177 \text{ mSv}\cdot\text{yr}^{-1}$) is well below the limit of $1 \text{ mSv}\cdot\text{yr}^{-1}$, indicating an absence of acute radiological risk for the population.
- The excess lifetime cancer risk (0.530×10^{-3}) is significantly higher than the global reference average, suggesting an increased probabilistic long-term risk.

In conclusion, while the current exposure does not warrant emergency measures, the variability in radiation levels and the higher-than-average long-term risk justify continued attention. These findings provide a crucial database for the development of future public health policies, particularly concerning the selection of locally sourced building materials and the mapping of agricultural areas to minimize worker exposure.

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